The VORTEX team

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- ***U. Uppsala***: M. Karlsson, P. Forsberg, P. Piron, E. Vargas Catalan
- ***Caltech/JPL***: D. Mawet, E. Serabyn, K. Matthews, G. Ruane, AJ Riggs, E. Choquet, M. Bottom, H. Ngo, R. Jensen-Clem
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OLIVIER ABSIL

FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

OUTLINE

history and technology development

commissioning & on-sky performance

scientific results

image processing with machine learning

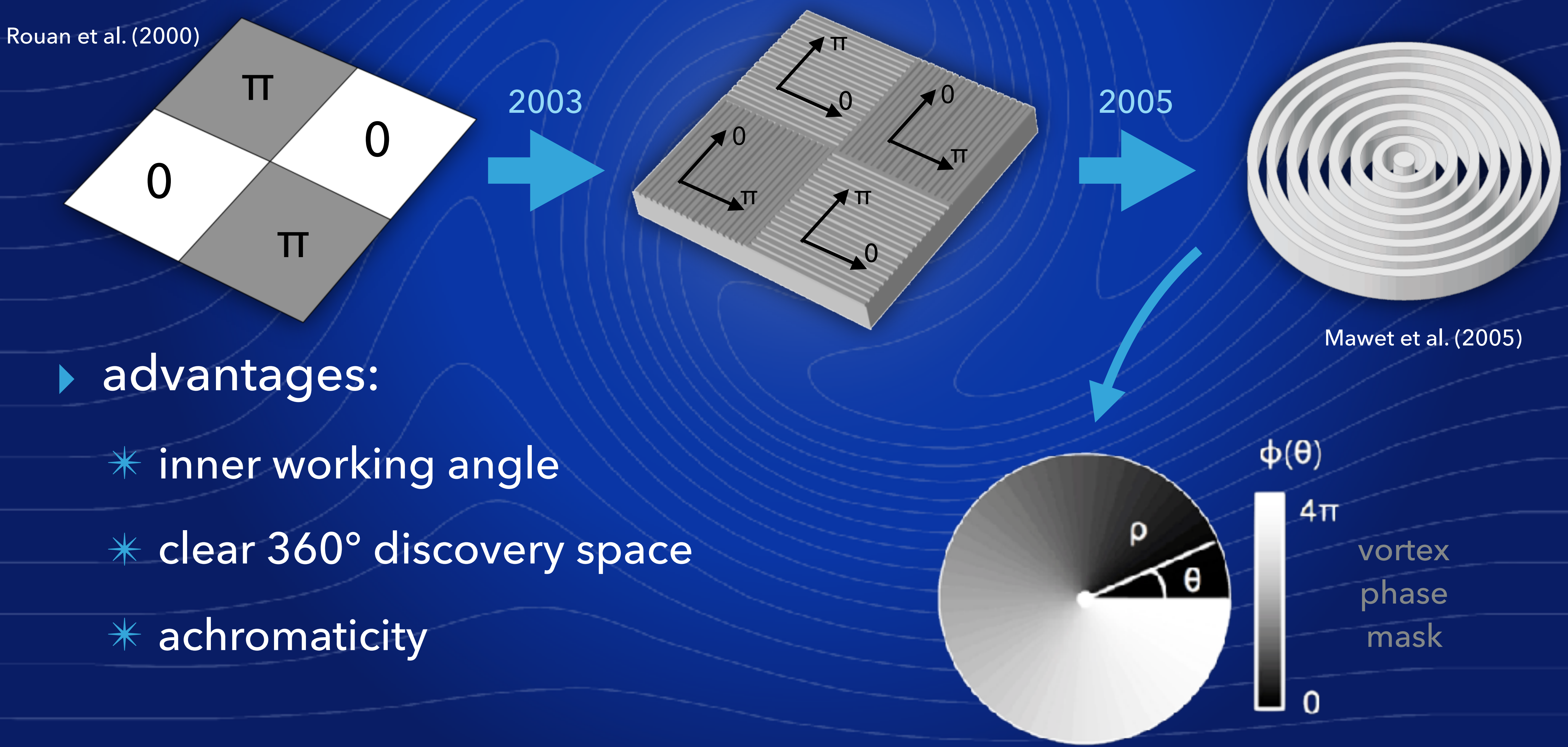
future projects

VORTEX

HISTORY AND TECHNOLOGY DEVELOPMENT

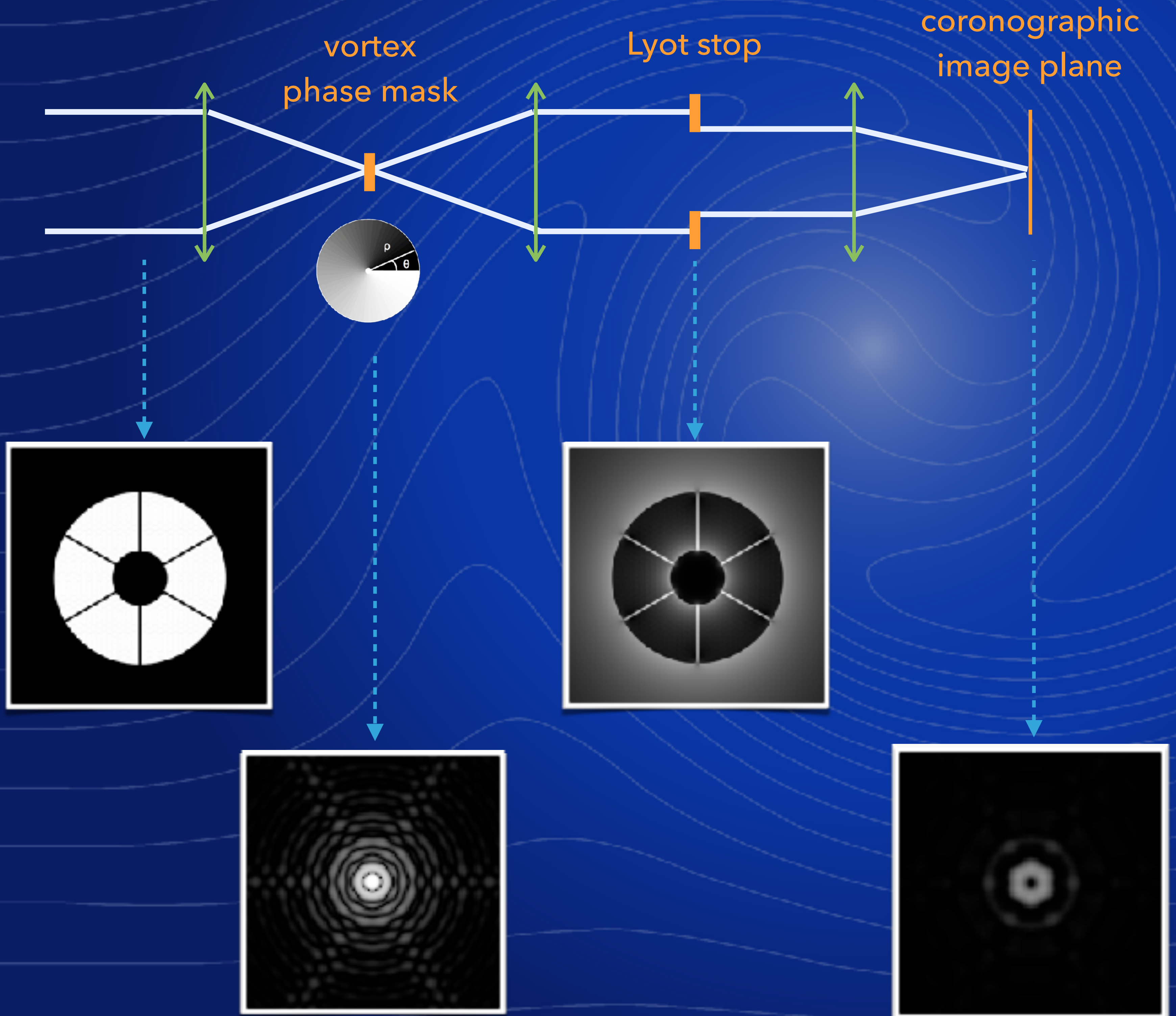
THE BIRTH OF A CONCEPT

- FQPM → sub-wavelength grating → annular groove phase mask

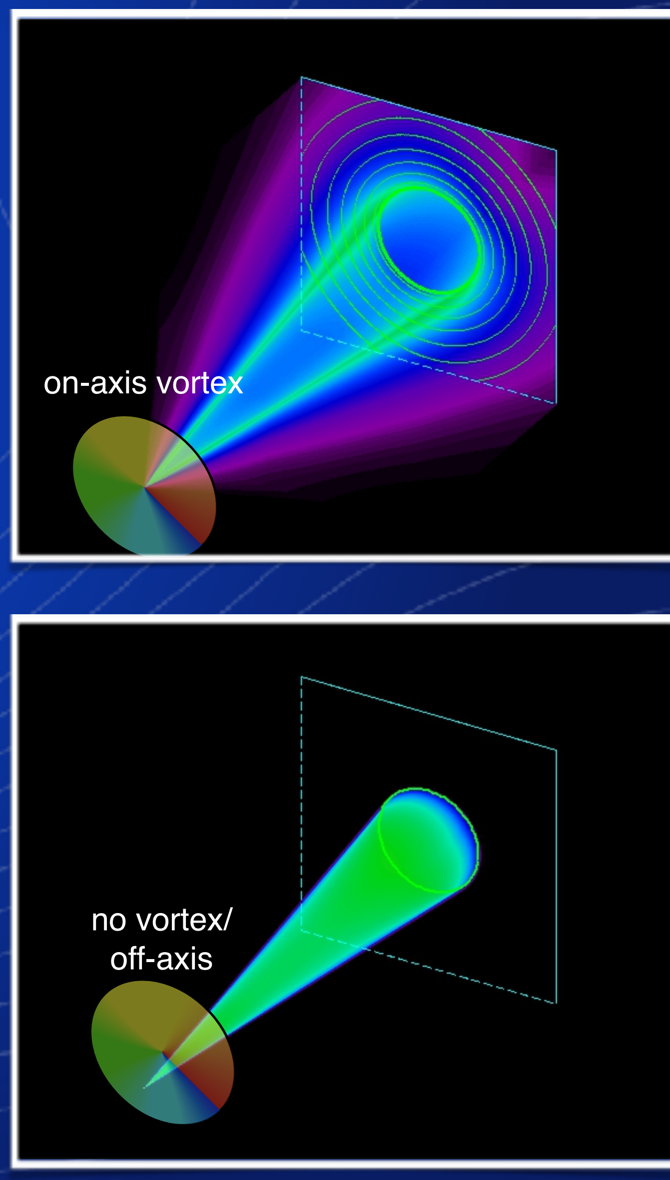


- advantages:
  - inner working angle
  - clear 360° discovery space
  - achromaticity

THE VORTEX CORONAGRAPH IN A NUTSHELL

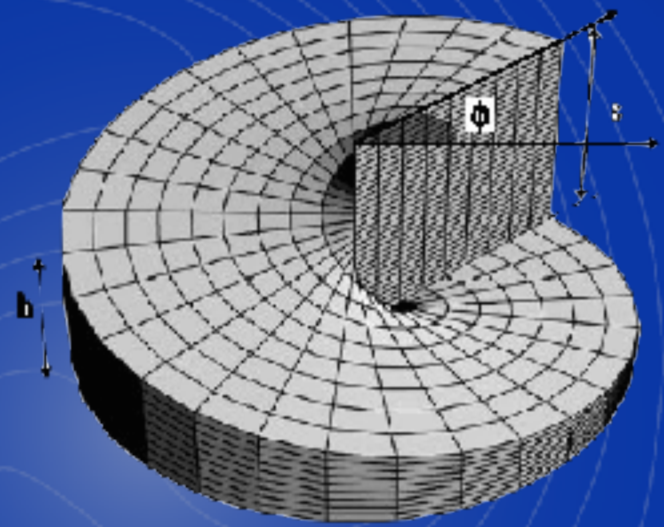


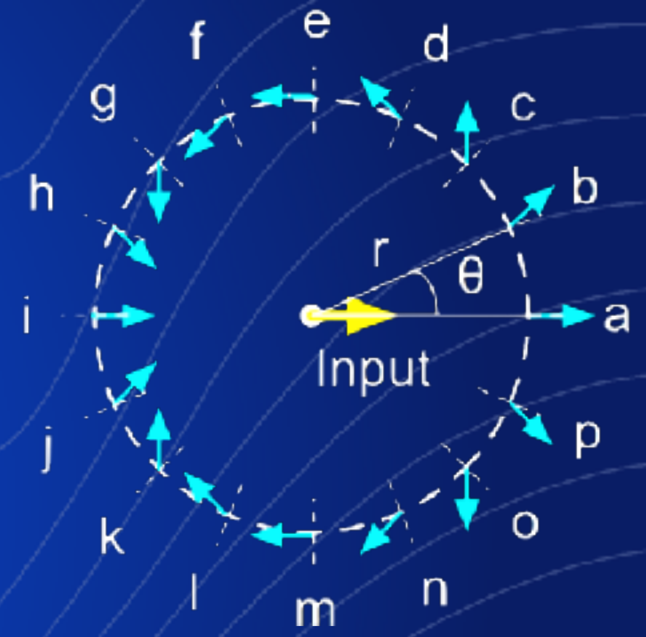
perfect on-axis cancellation
for a circular aperture



IMPLEMENTATIONS OF THE VORTEX PHASE MASK

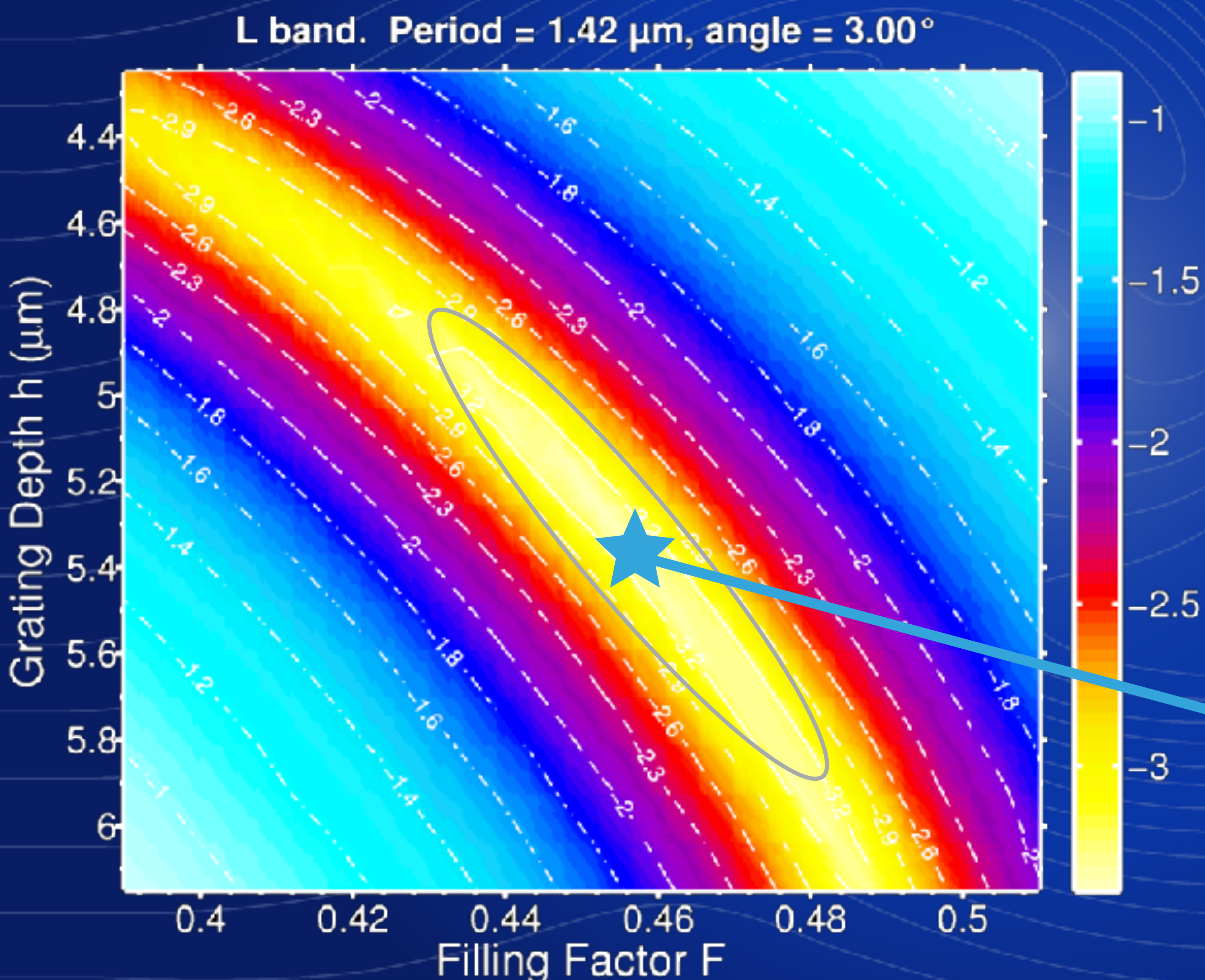
- scalar vortex
  - helical piece of glass
- vector vortex
  - liquid crystal polymers
  - subwavelength gratings
  - photonic crystals

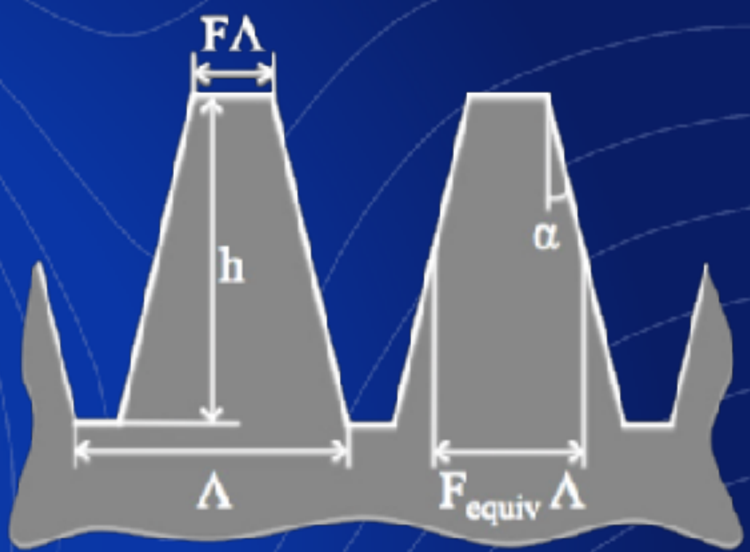


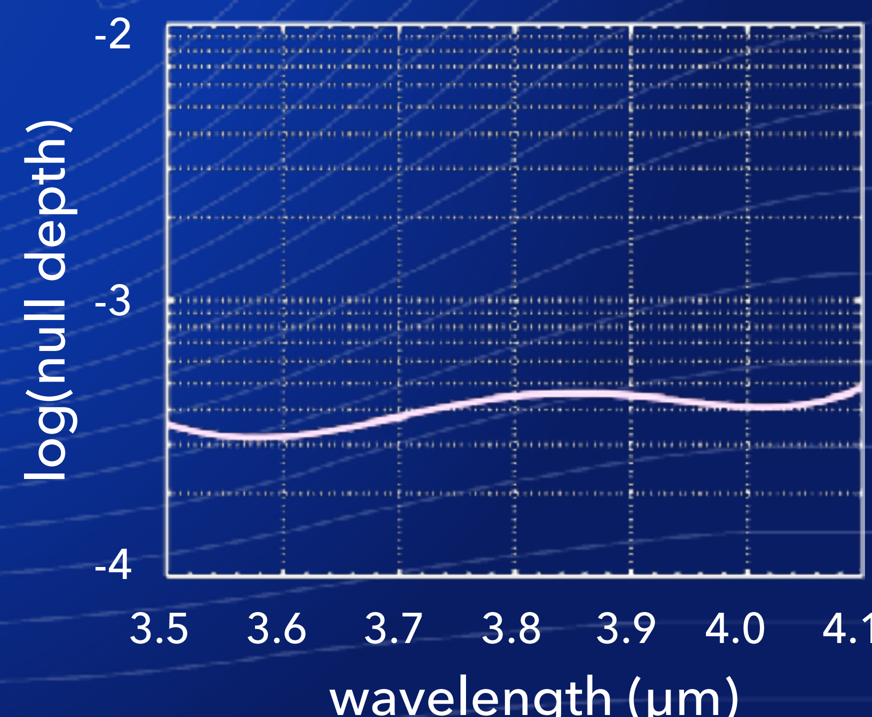


Annular Groove Phase Mask

OPTIMIZING THE GRATING DESIGN





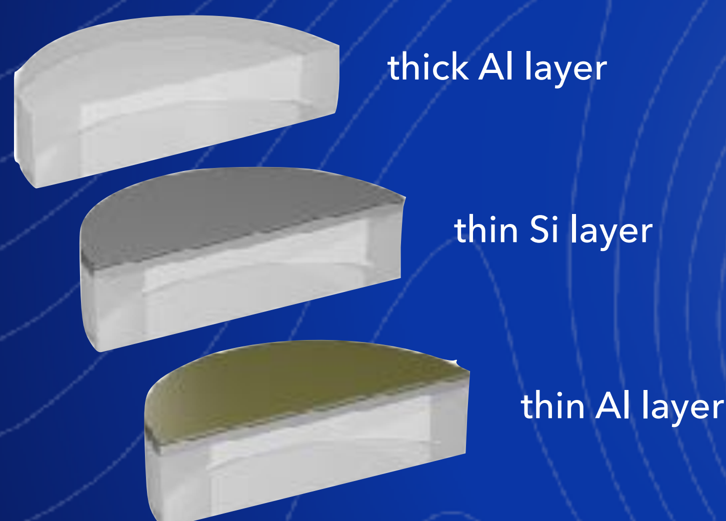


Delacroix et al. (2013)

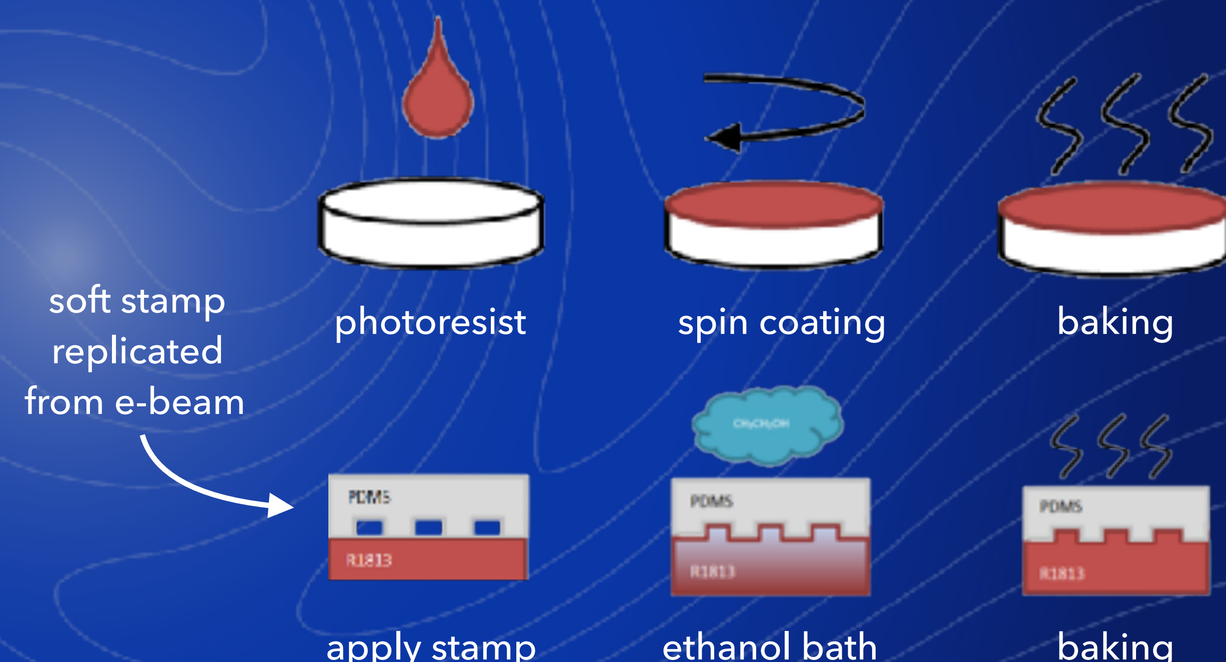
MANUFACTURING DIAMOND AGPM @ UPPSALA

Vargas Catalan et al. (2016)

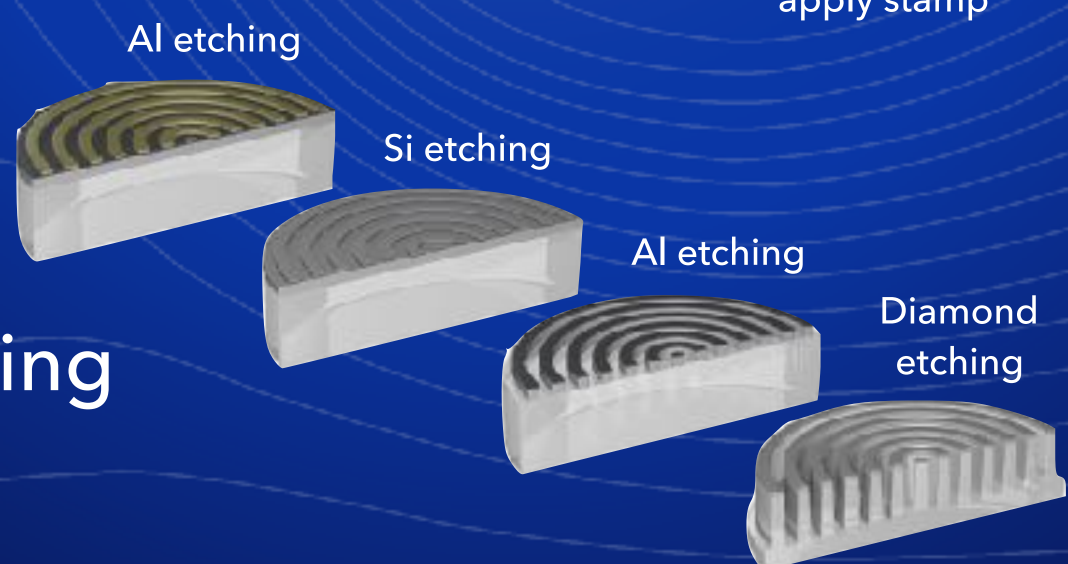
1. diamond coated with Al and Si layers (sputtering)

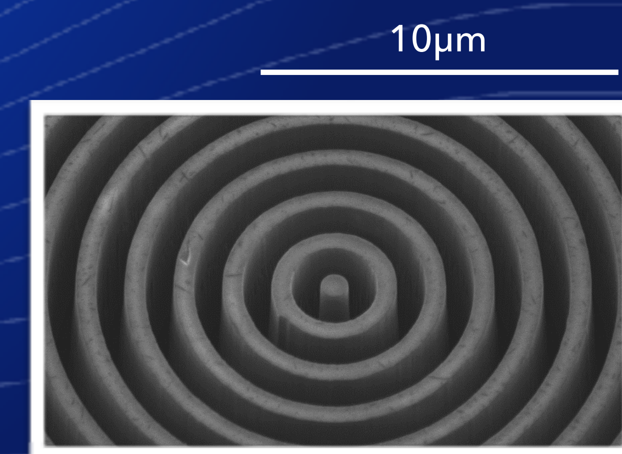


2. e-beam pattern transferred with solvent-assisted moulding

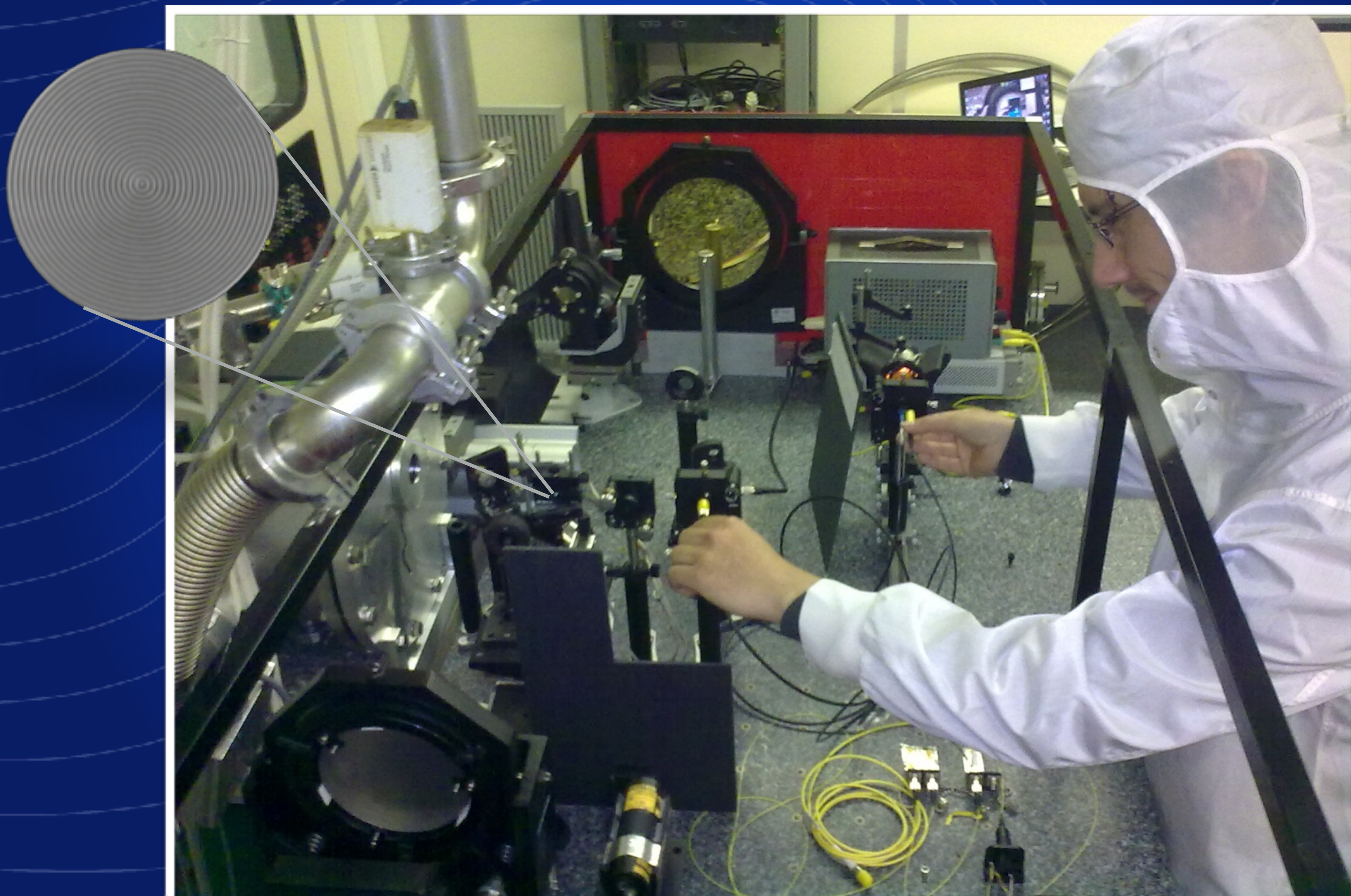


3. reactive ion etching



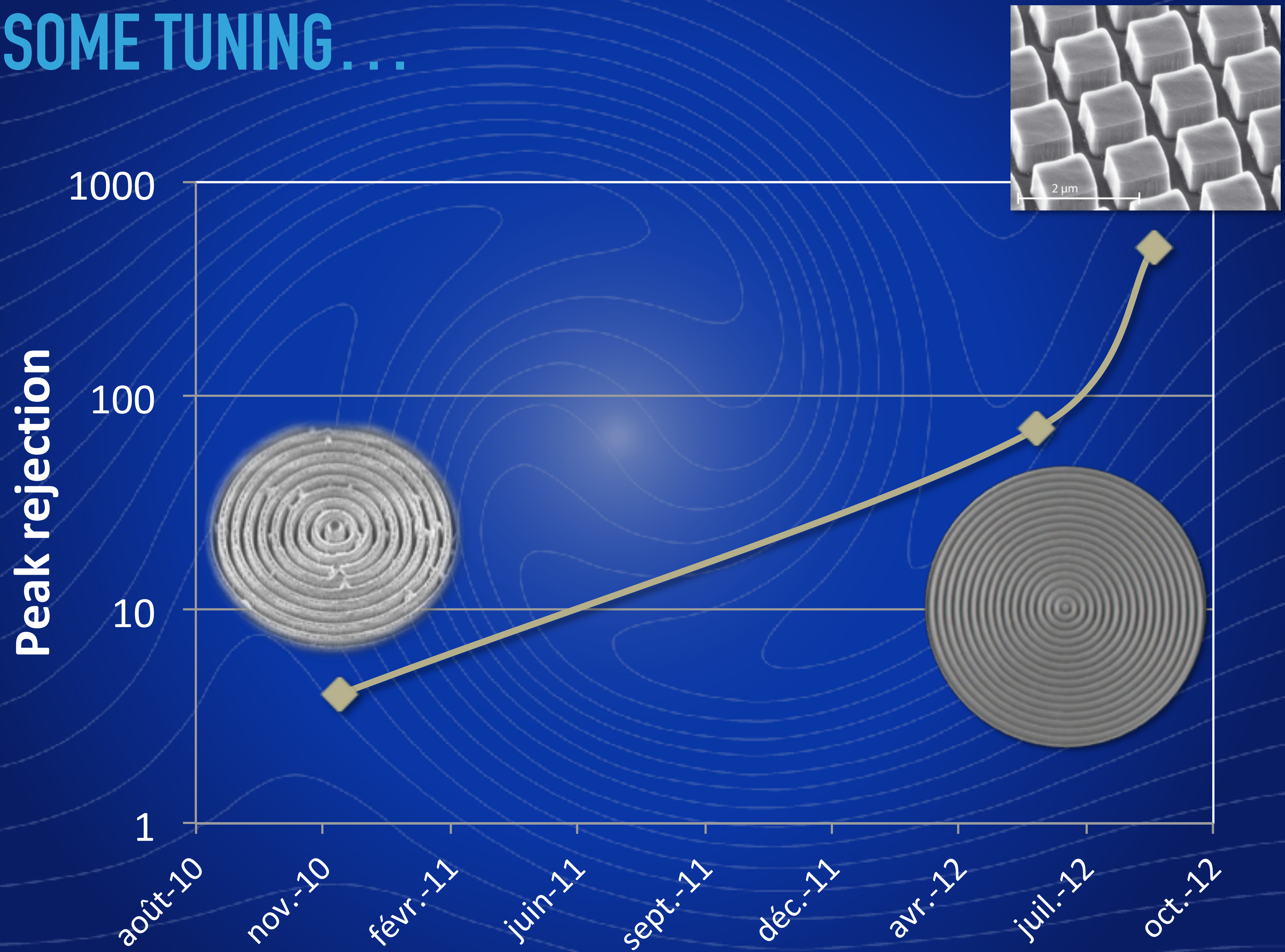


SETTING UP THE « YACADIRE » BENCH @ MEUDON

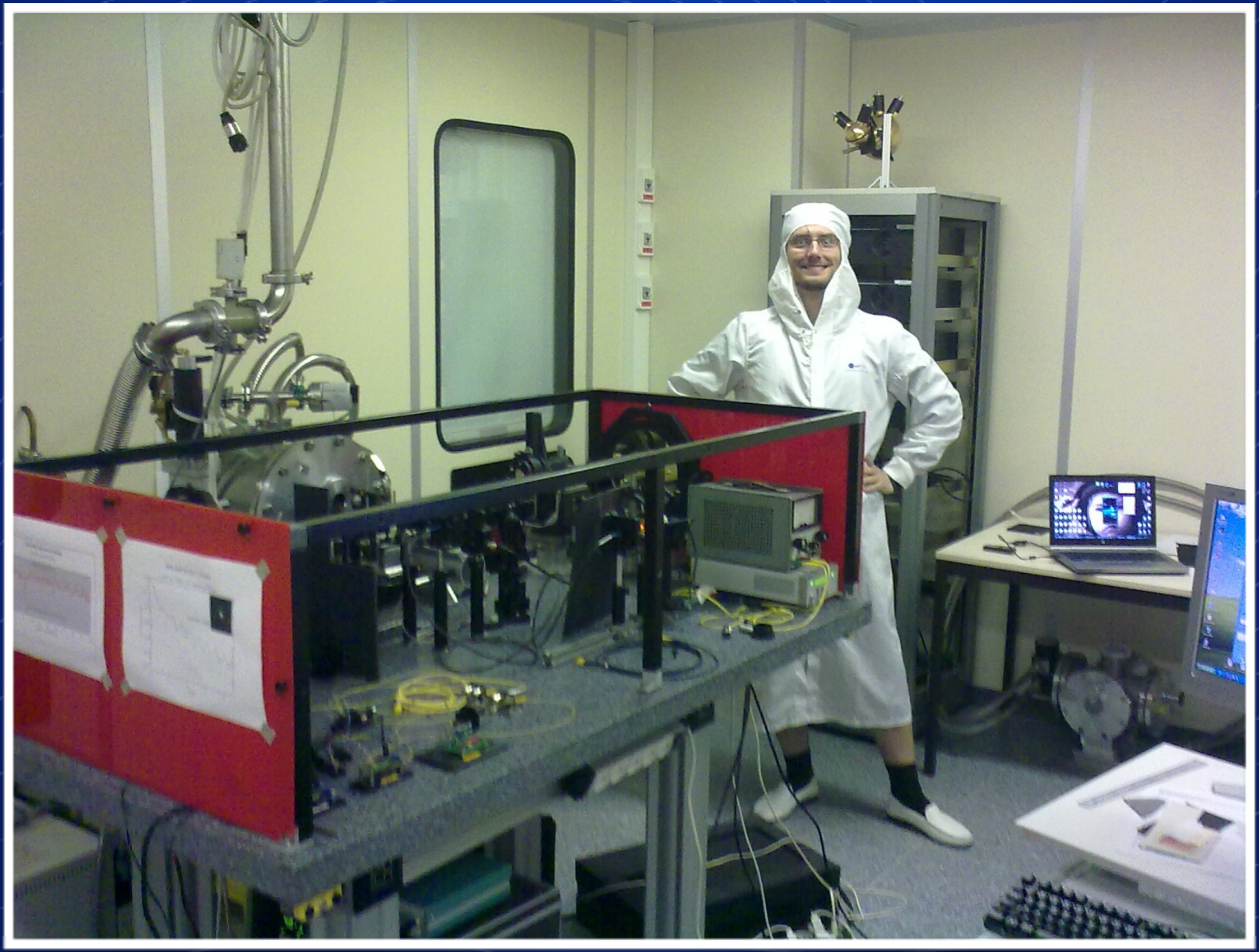


ANGUISH…

AFTER SOME TUNING…

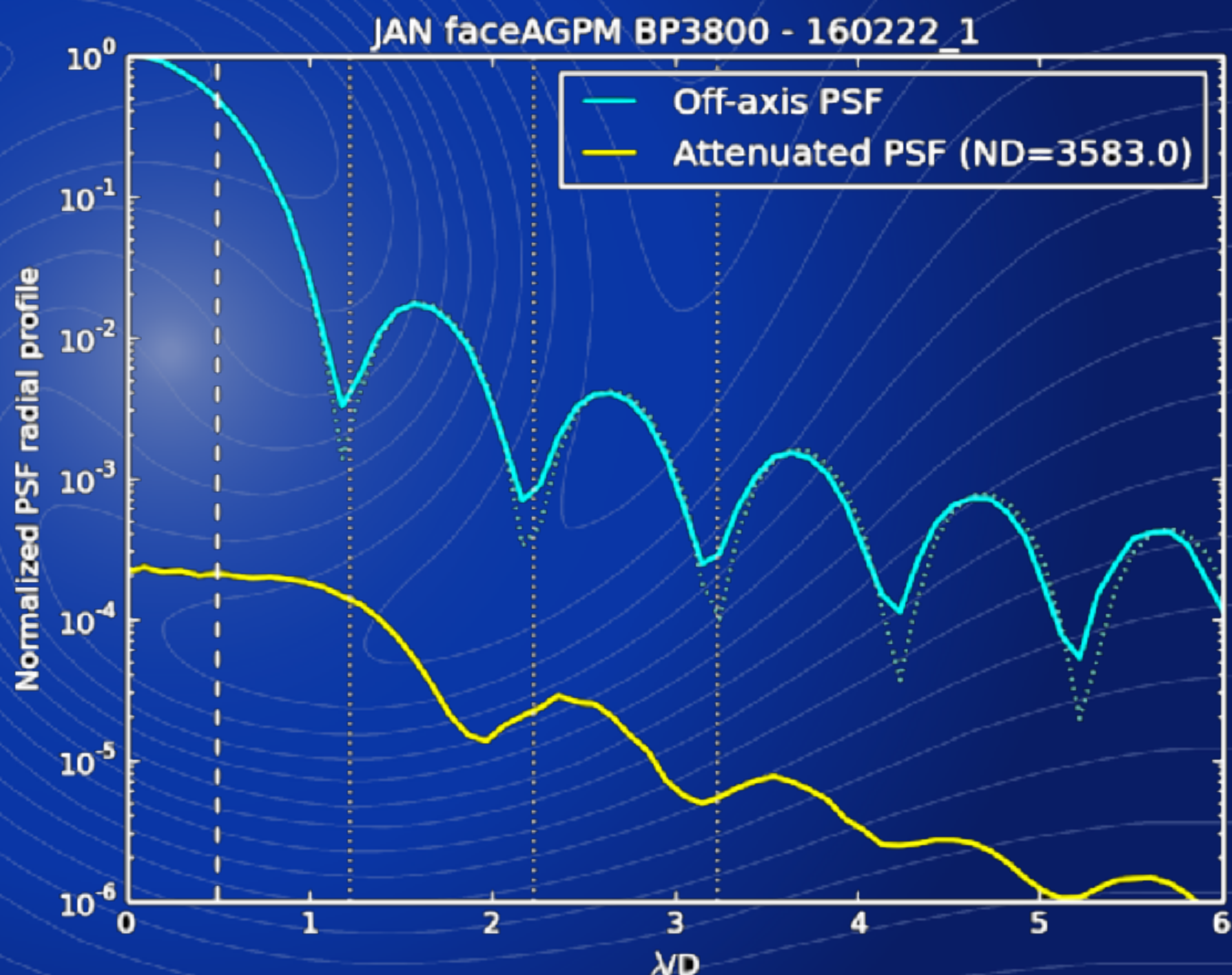


BLISS!



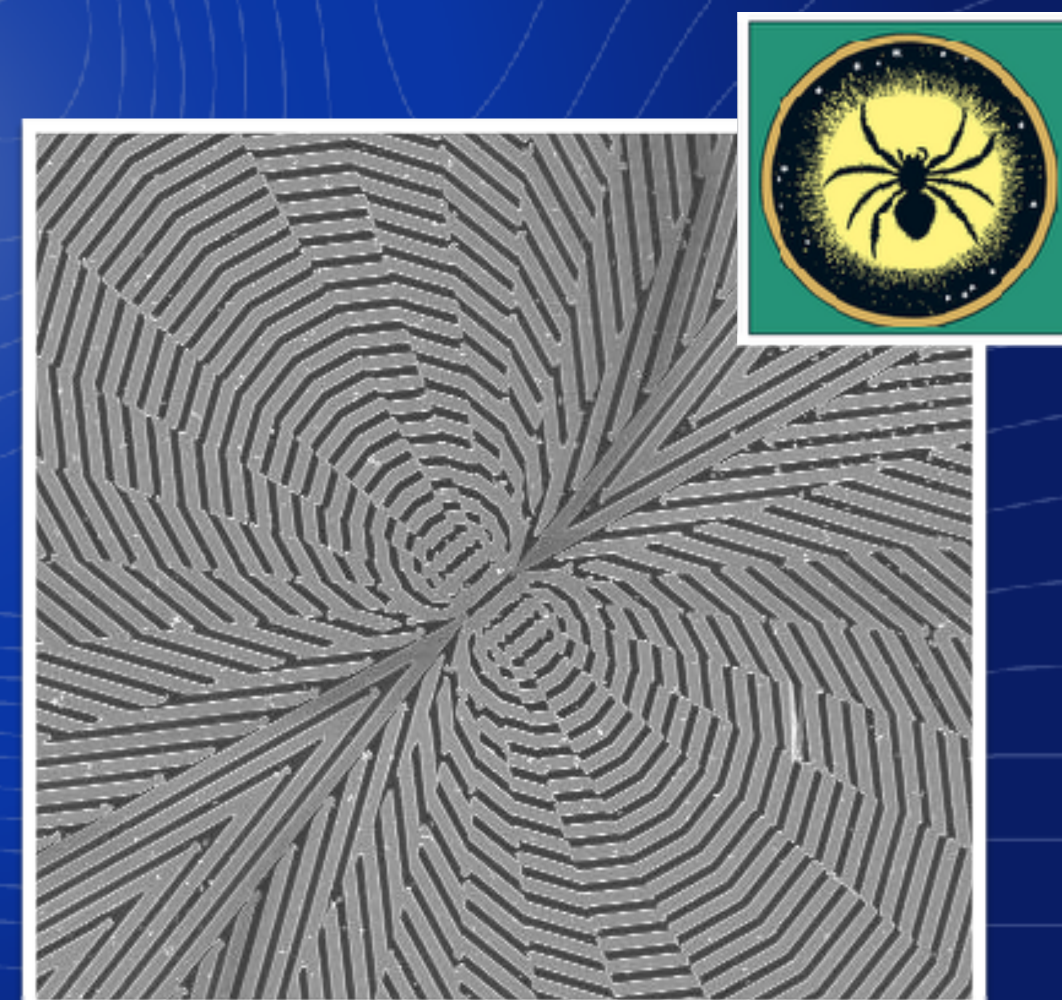
BEST PERFORMANCE IN THE LAB – 2017 UPDATE

- dedicated test bench (VODCA) now available at ULiège
- 10+ science-grade L-band AGPMs etched & tested
- broadband rejection up to 1500 : 1



EXTENDING THE CONCEPT

- AGPM first developed for thermal infrared (L, M, N bands)
  - excellent performance on ~30% bandwidth
- manufacturing tests for H-K bands promising, but work remains to be done
- now exploring higher topological charges
  - less sensitive to tip-tilt, at the expense of larger IWA



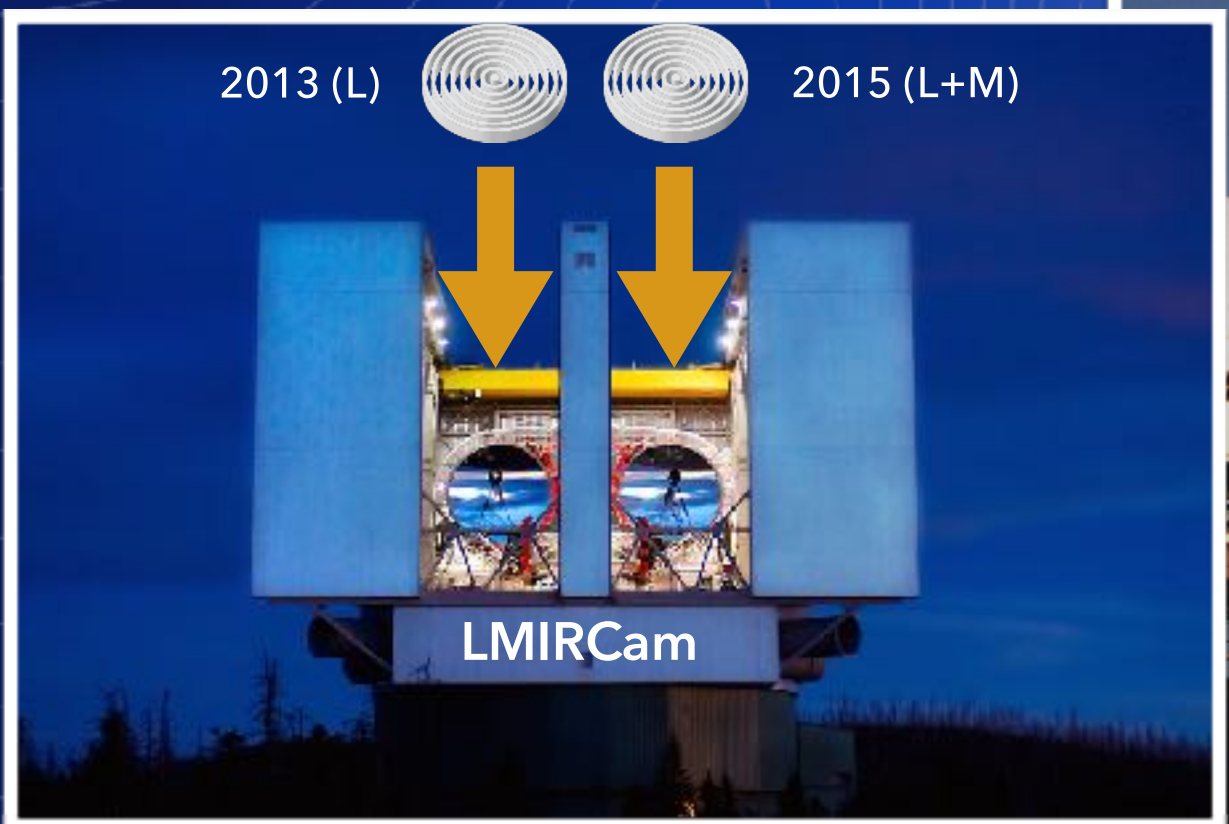
work in progress

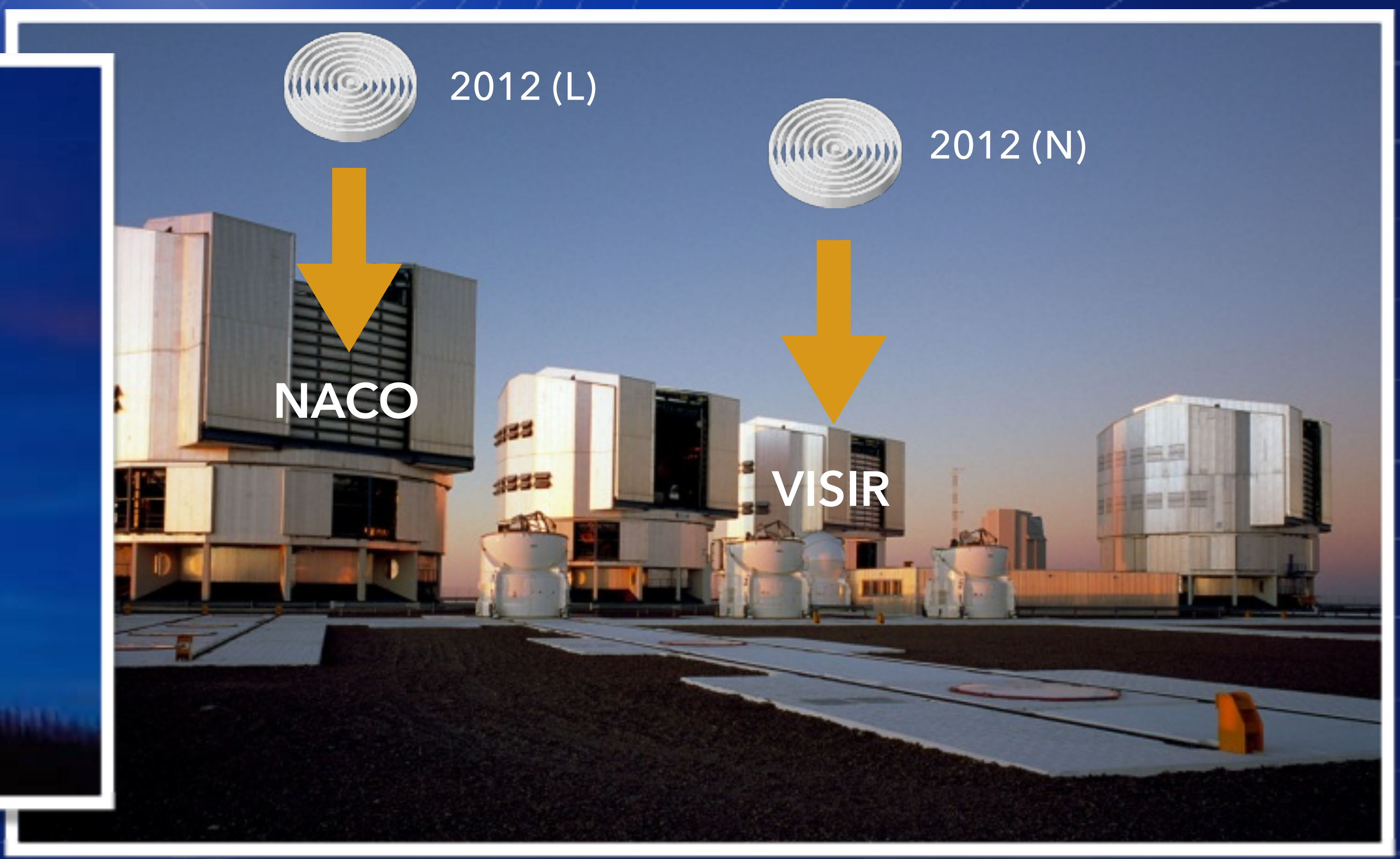
VORTEX

COMMISSIONING & ON-SKY PERFORMANCE

INSTALLATION AND COMMISSIONING

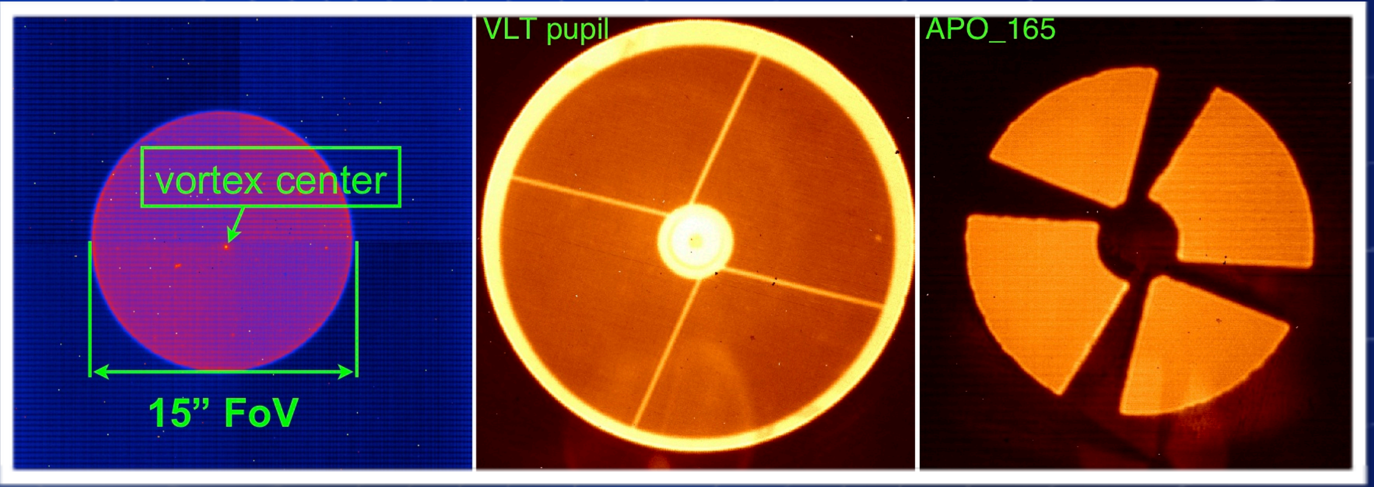
- piggyback on existing coronagraphic IR cameras
- very short commissioning phase (1-2 nights)



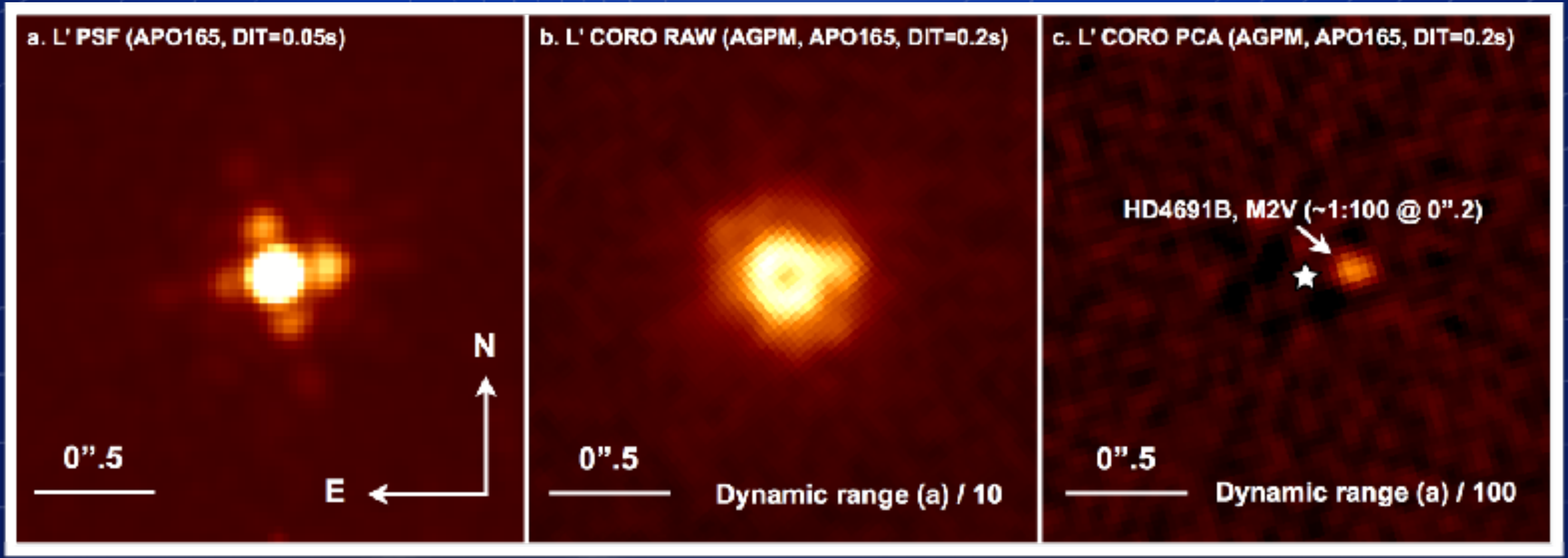


AGPM FIRST LIGHT @ NACO (DEC 2012)

- worked out of the box with available Lyot stops
- serendipitous discovery of M2V at 2λ/D from F0V

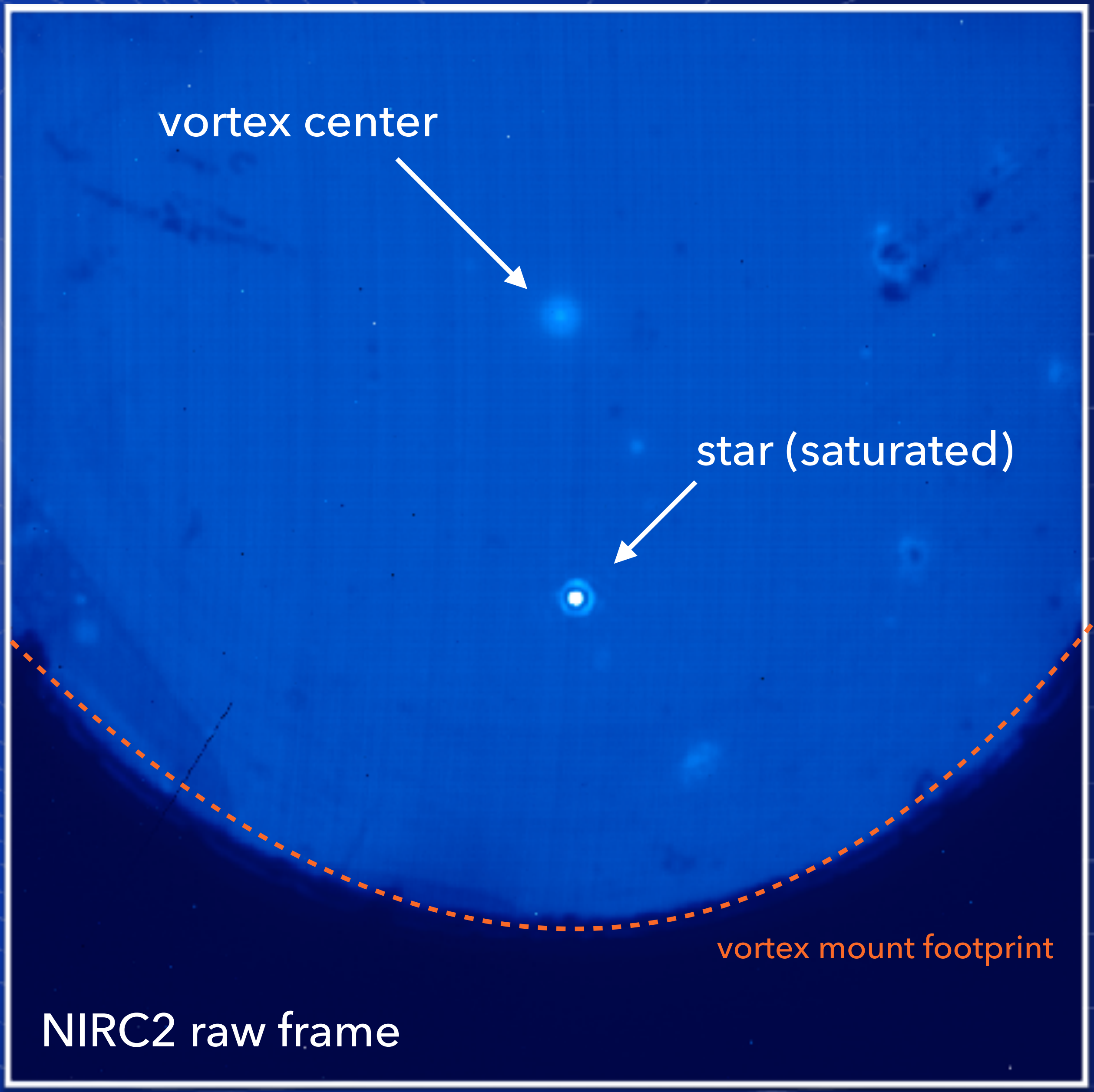


Mawet et al. (2013)



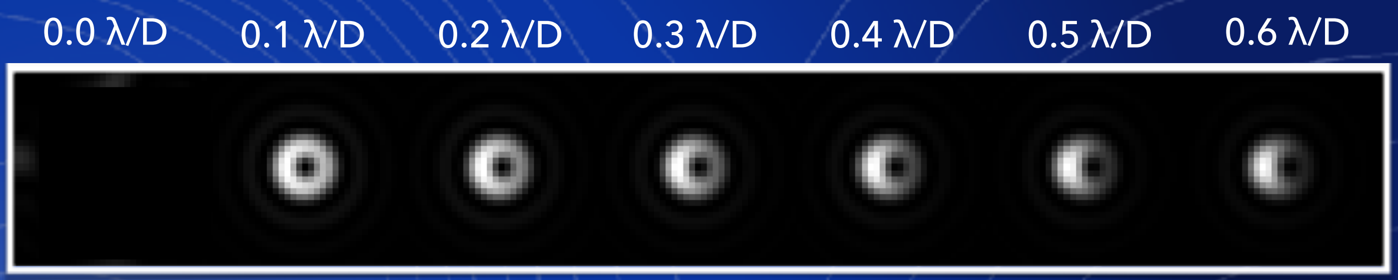
ON-SKY OPERATIONS: THE VORTEX GLOWS!

- thermal emission outside pupil partly diffracted inside pupil by vortex
- seen in all instruments (vortex upstream cold stop)
- removed by background subtraction
- useful for centering

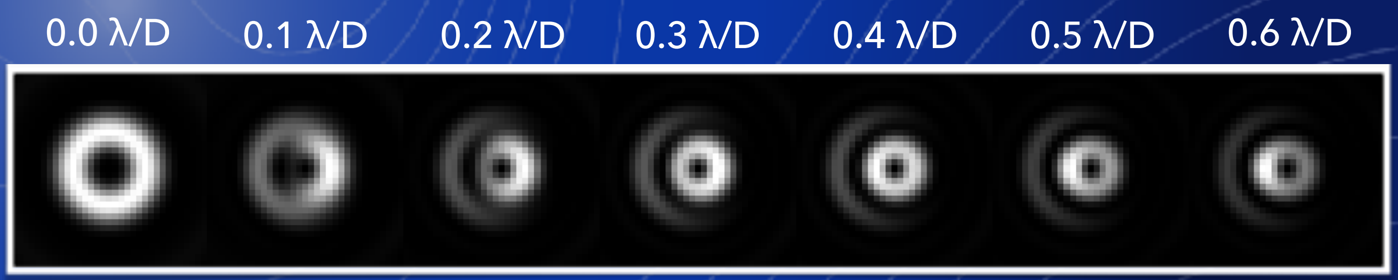


ON-SKY OPERATIONS: ACQUISITION & CENTERING

- pointing errors create asymmetric « donut »
- central obstruction changes the expected behavior of the donut
- need modeling to infer pointing error from image (QACITS algorithm)
- can be used to control pointing at low frequency



w/o central obstruction

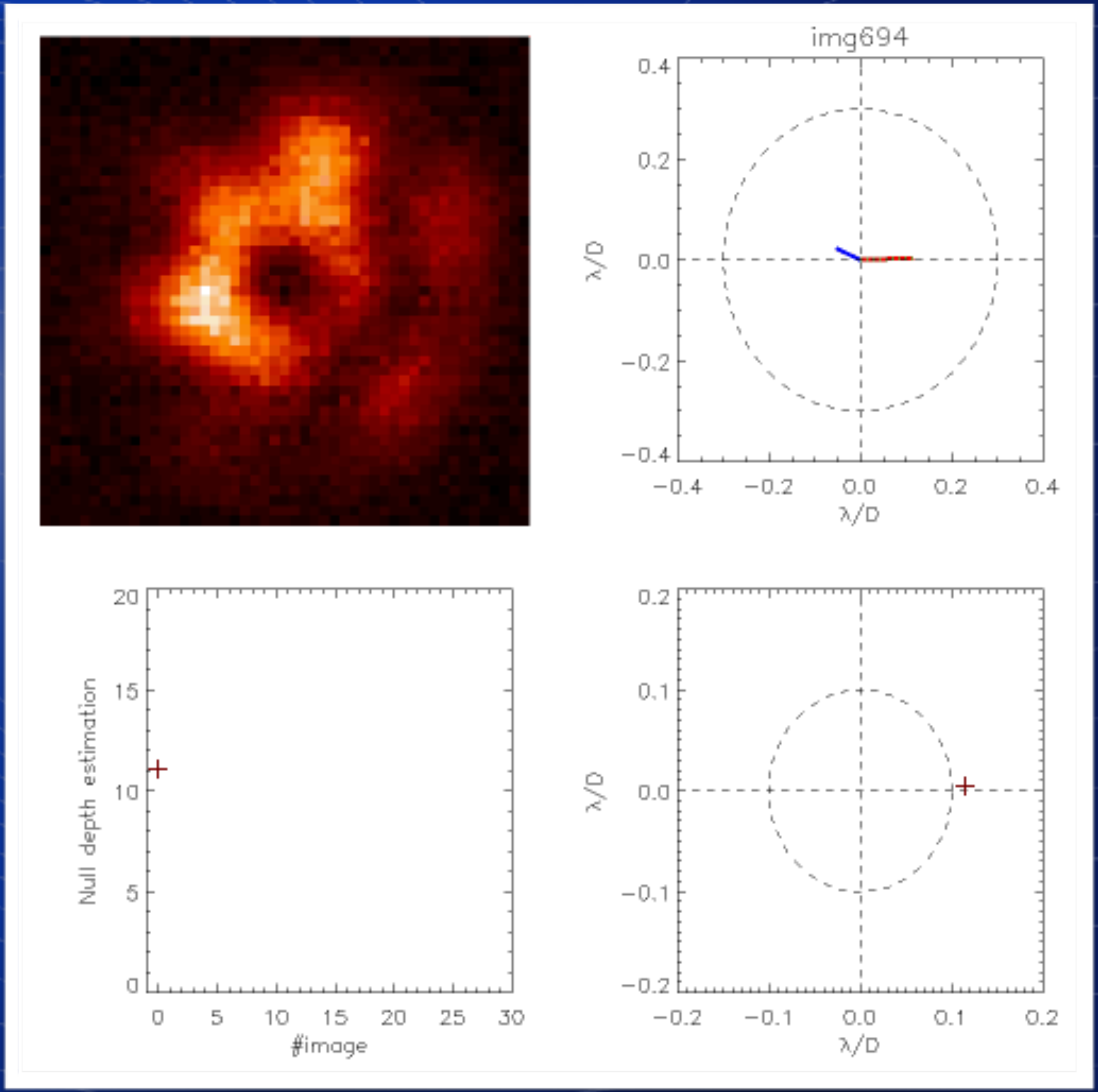


w/ central obstruction

Huby et al. 2015

CLOSED-LOOP CENTERING CONTROL

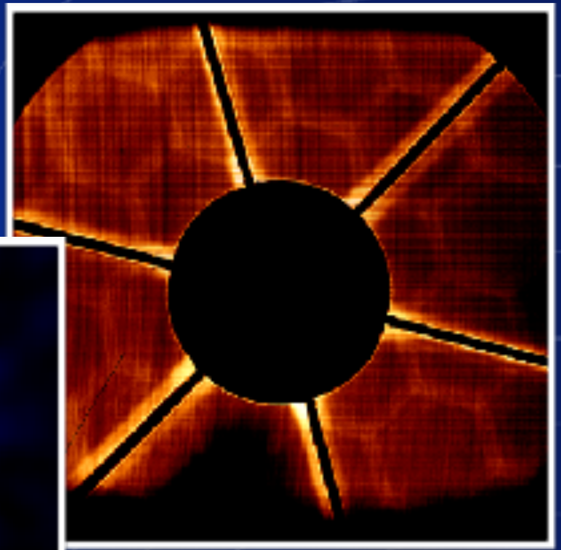
- fully automated vortex operations with QACITS validated on NIRC2
  - includes acquisition & calibration
- ensures consistant centering and data quality
- rms jitter ~ 0.02 λ/D (@ 0.03 Hz)



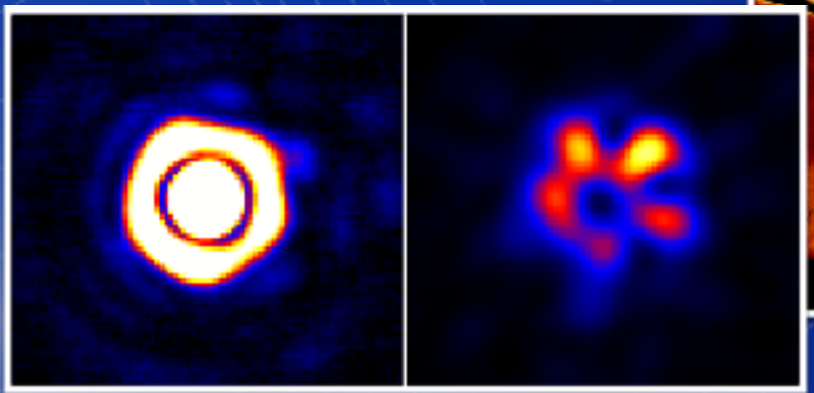
ON-SKY STARLIGHT CANCELLATION @ NIRC2

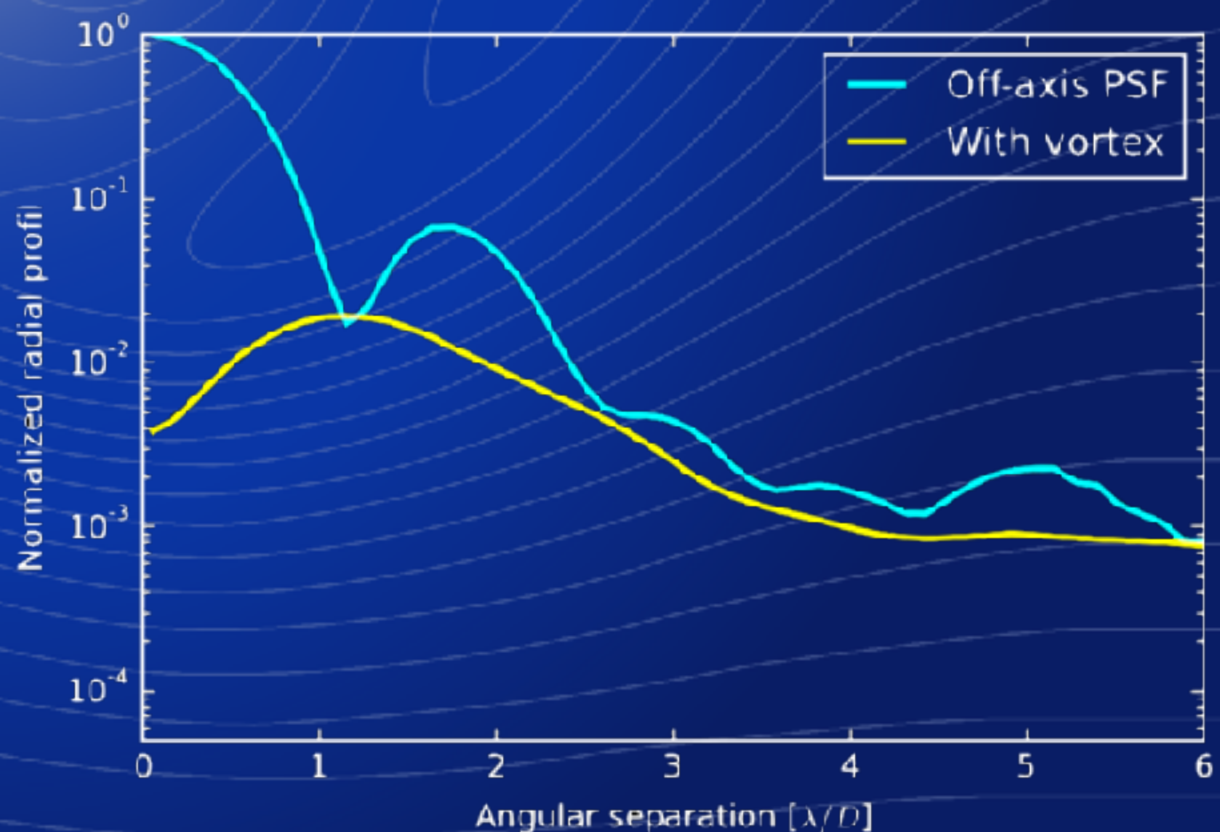
- on-sky extinction limited by
  - pupil geometry / Lyot stop
  - AO residuals
  - non-common path aberrations
- daytime speckle nulling helps reduce NCPA … but NIRC2 upgrade needed!

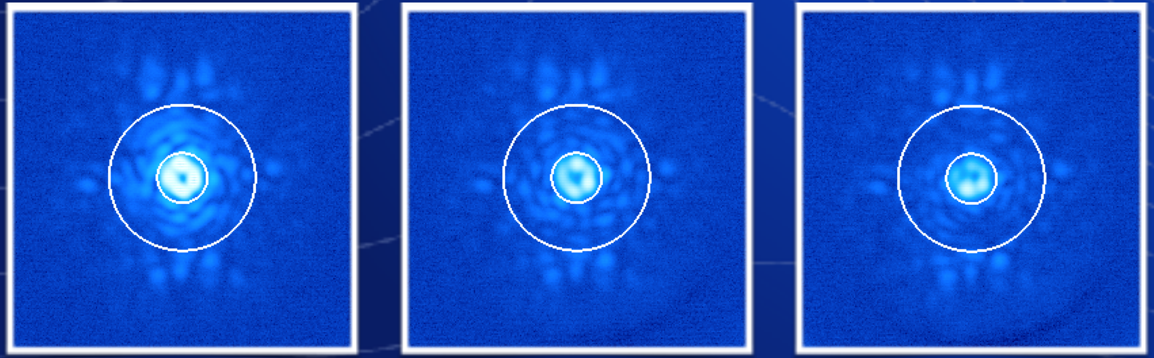
pupil after Lyot stop



PSF w/o vortex PSF w/ vortex



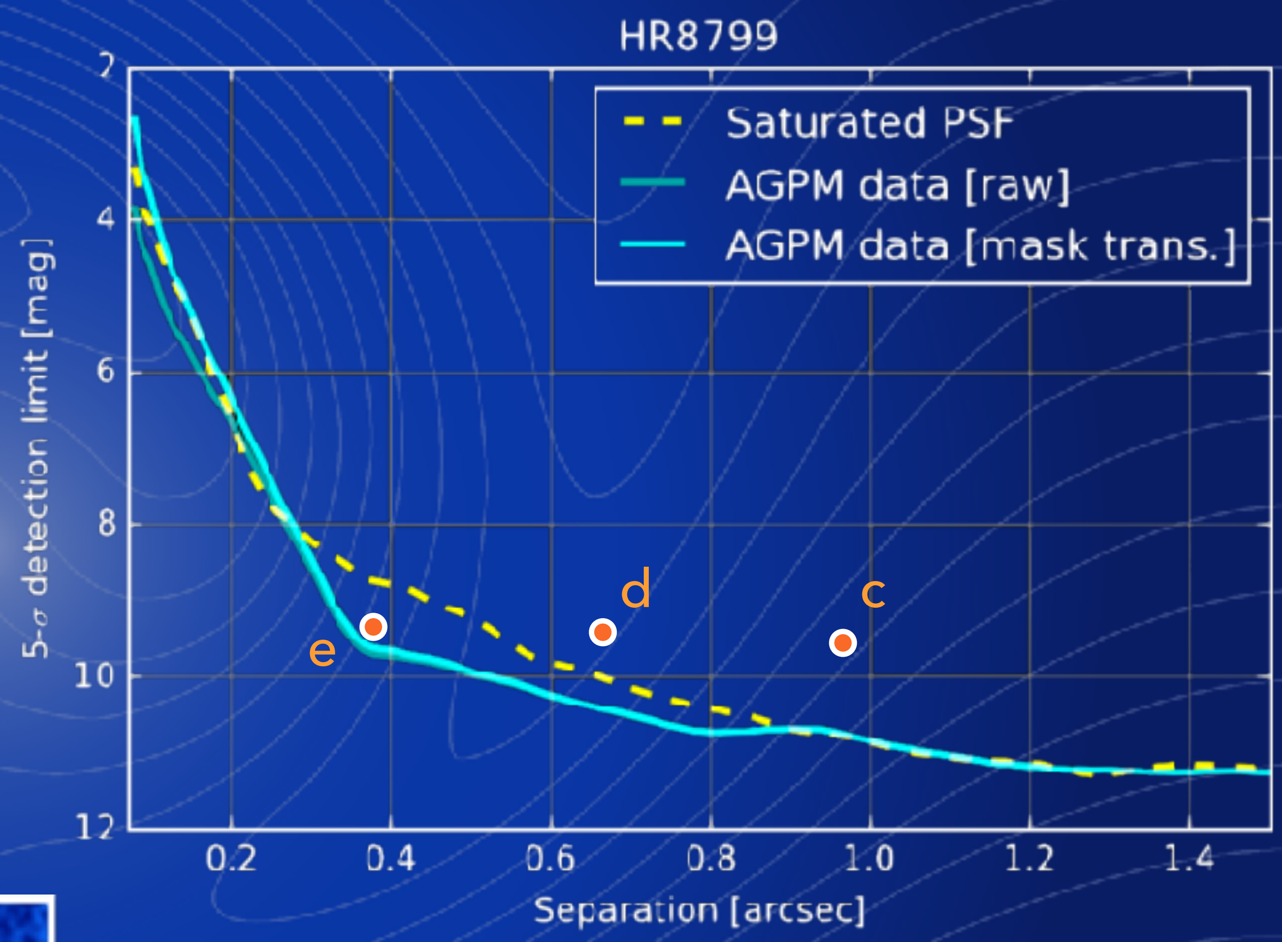




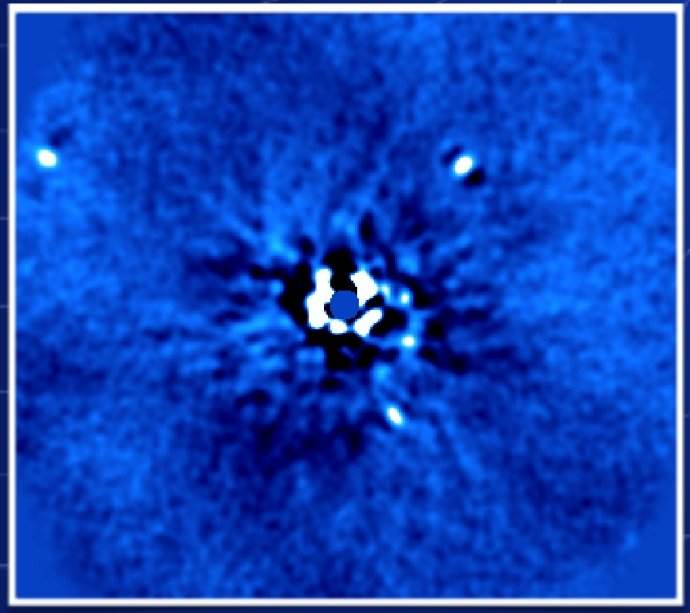
Bottom et al. (in prep)

IMPROVEMENT IN DETECTION LIMITS @ NIRC2

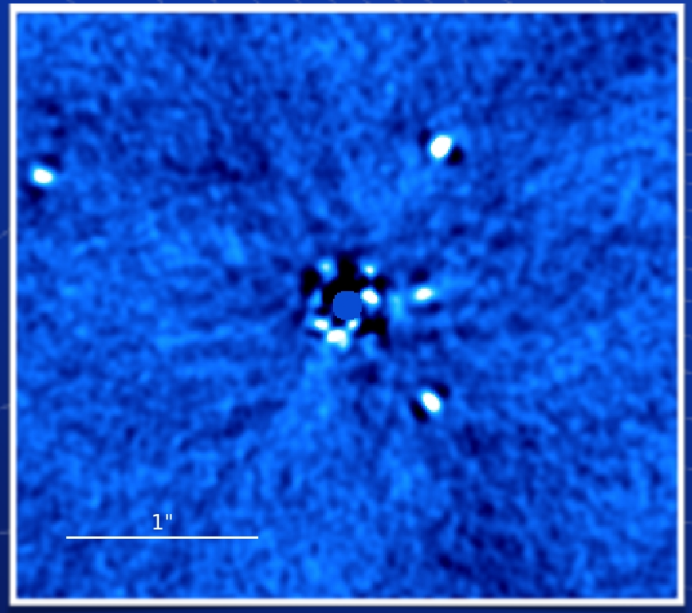
- obvious gain in 3–10 λ/D region (0.25" – 0.8")
- vortex transmission detrimental @ 1-2 λ/D



saturated imaging

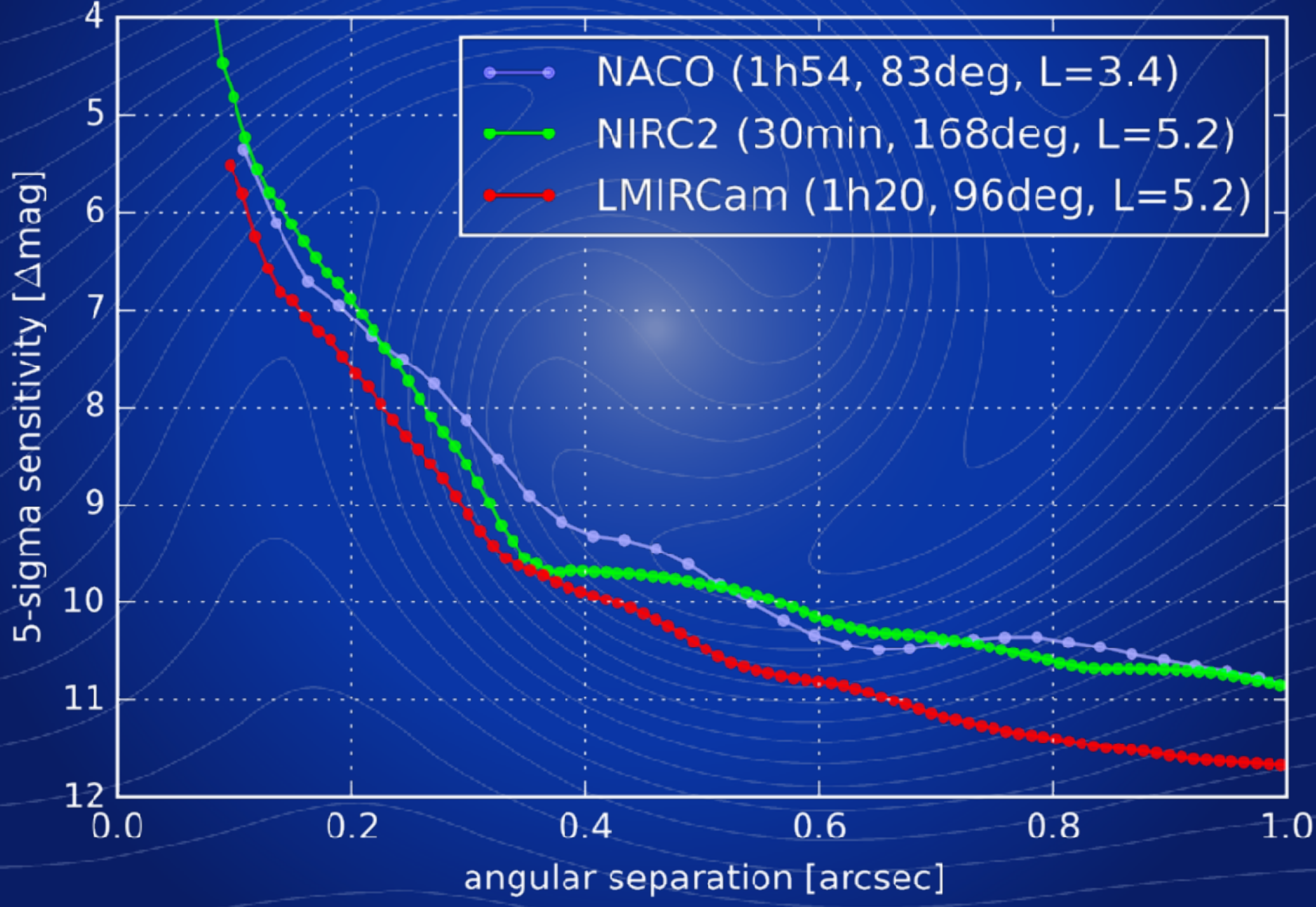


vortex imaging



comparison based on two HR8799 data sets with similar integration time and parallactic angle rotation, processed using a standard PCA-ADI algorithm

VORTEX PERFORMANCE ON VARIOUS INSTRUMENTS



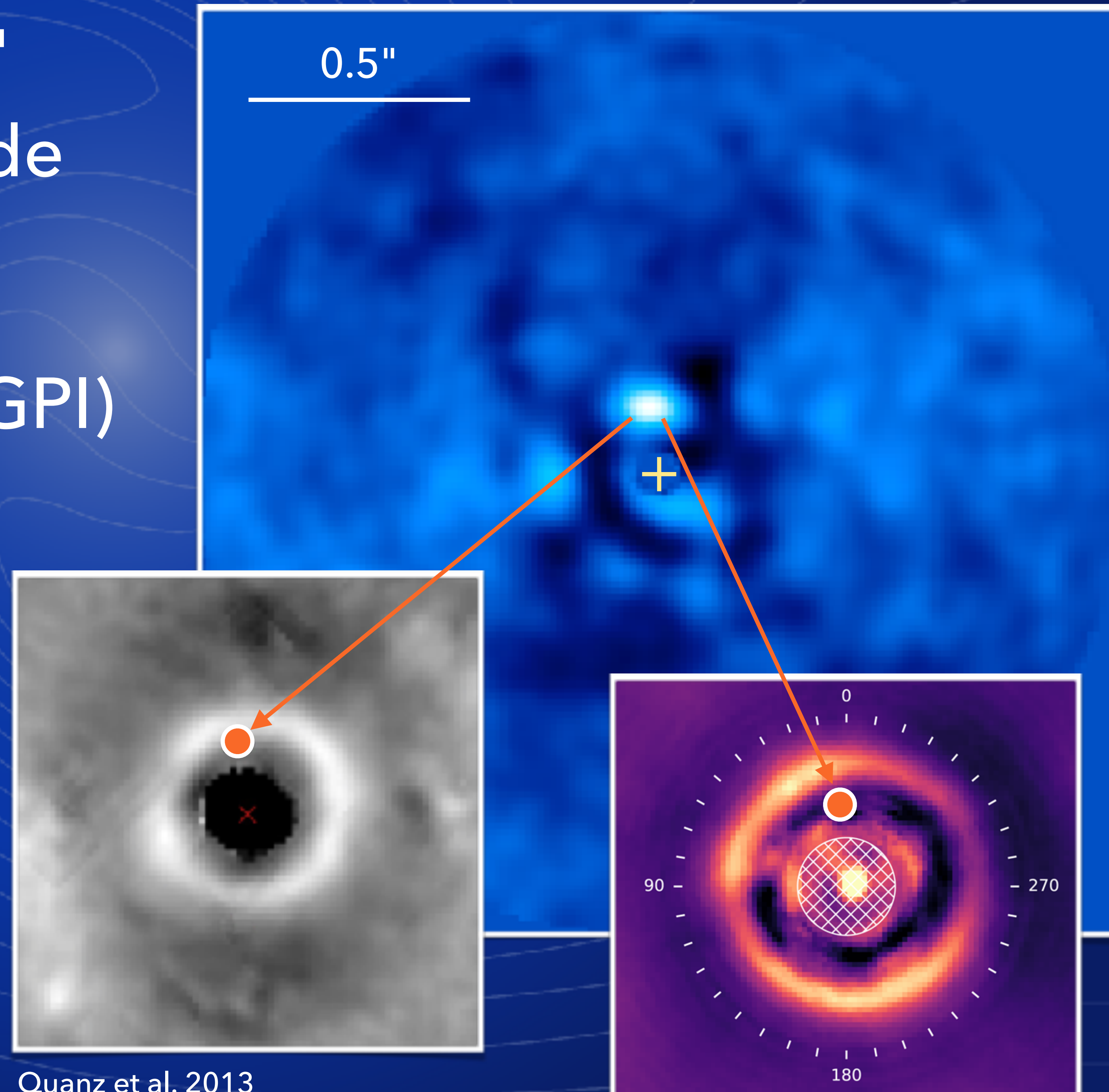
VORTEX

SCIENTIFIC RESULTS

EARLY SCIENCE @ VLT/NACO: HD 169142

- point-like source at 0.15" from Herbig Ae star, inside H-band PDI inner cavity
- not detected at J band (GPI) nor H-K bands (MagAO)
- possible explanations
  - accreting protoplanet?
  - disk feature?

Biller et al. 2014, Reggiani et al. 2014



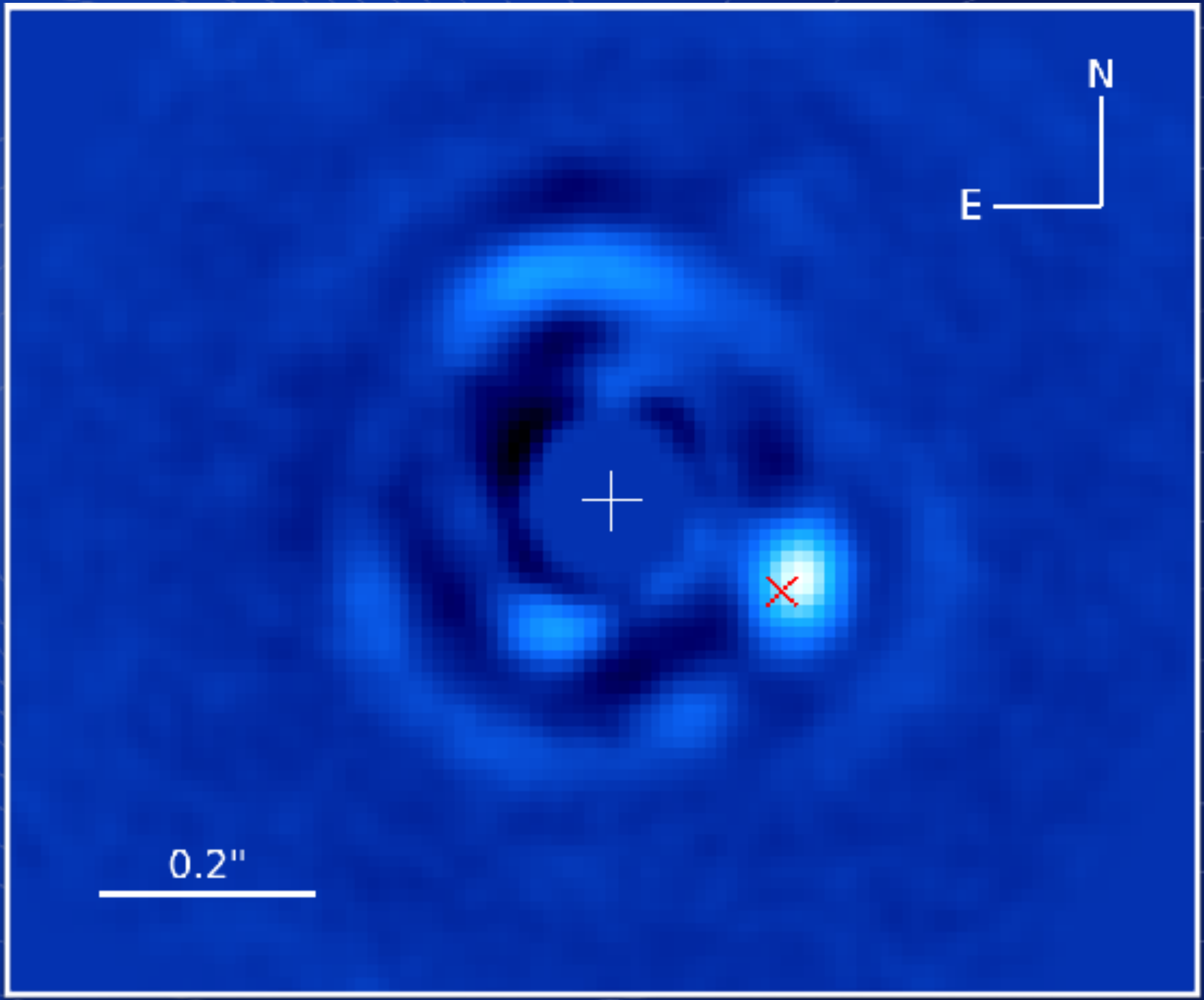
Quanz et al. 2013

Ligi et al. 2018

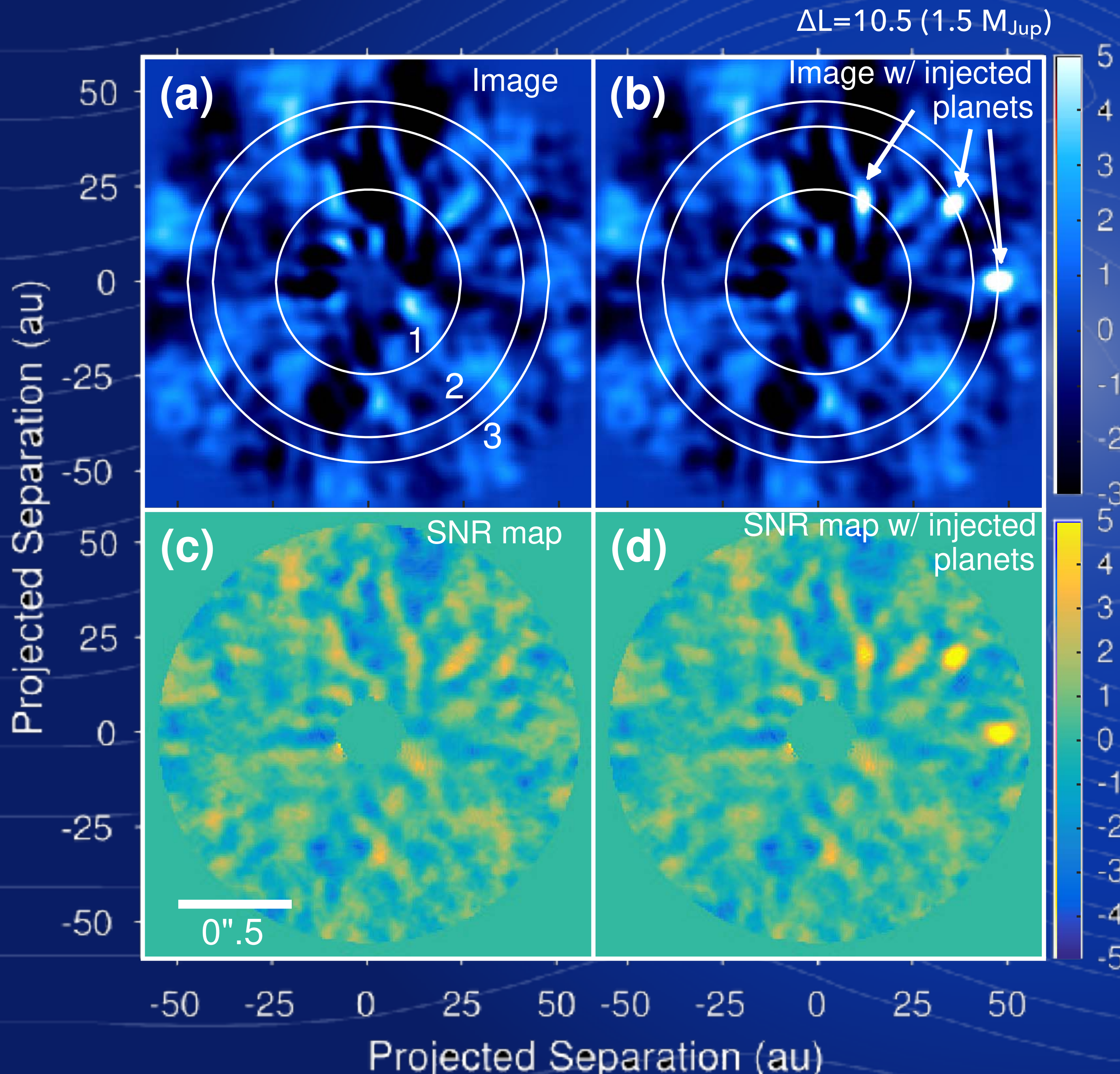
FIRST LIGHT @ KECK/NIRC2: HIP 79124

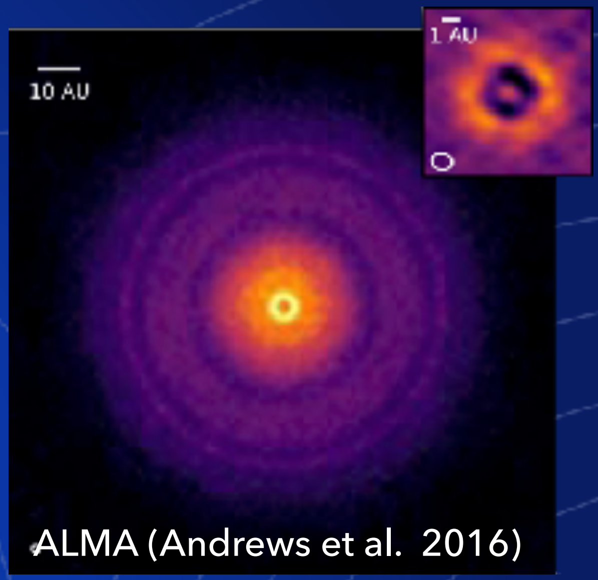
- brown dwarf around Sco-Cen A0 star
- 177 mas, ΔL=4.3
- only detected with aperture masking so far
- recovered with NIRC2+vortex during commissioning

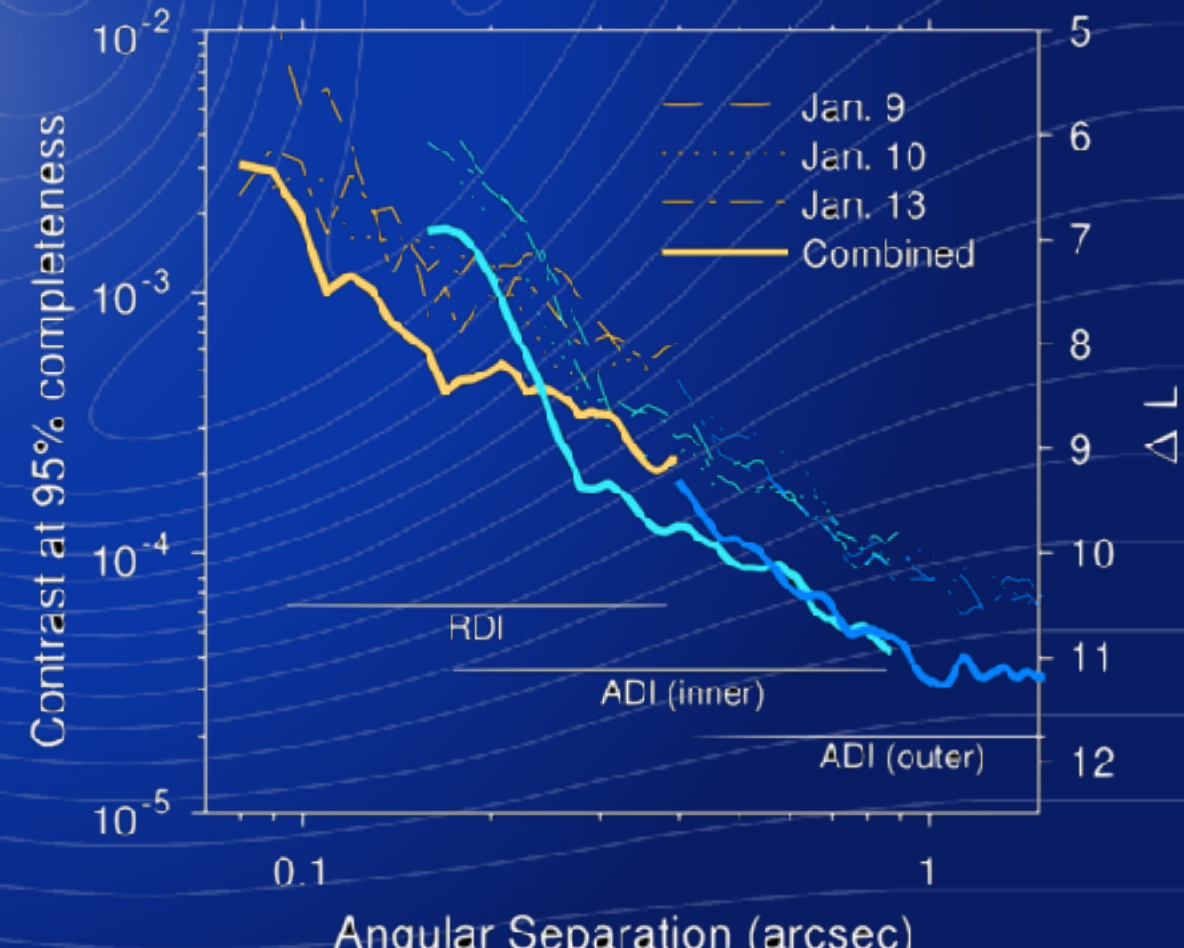
Serabyn et al. (2017)



KECK CORONAGRAPHIC DEEP FIELD: TW HYA





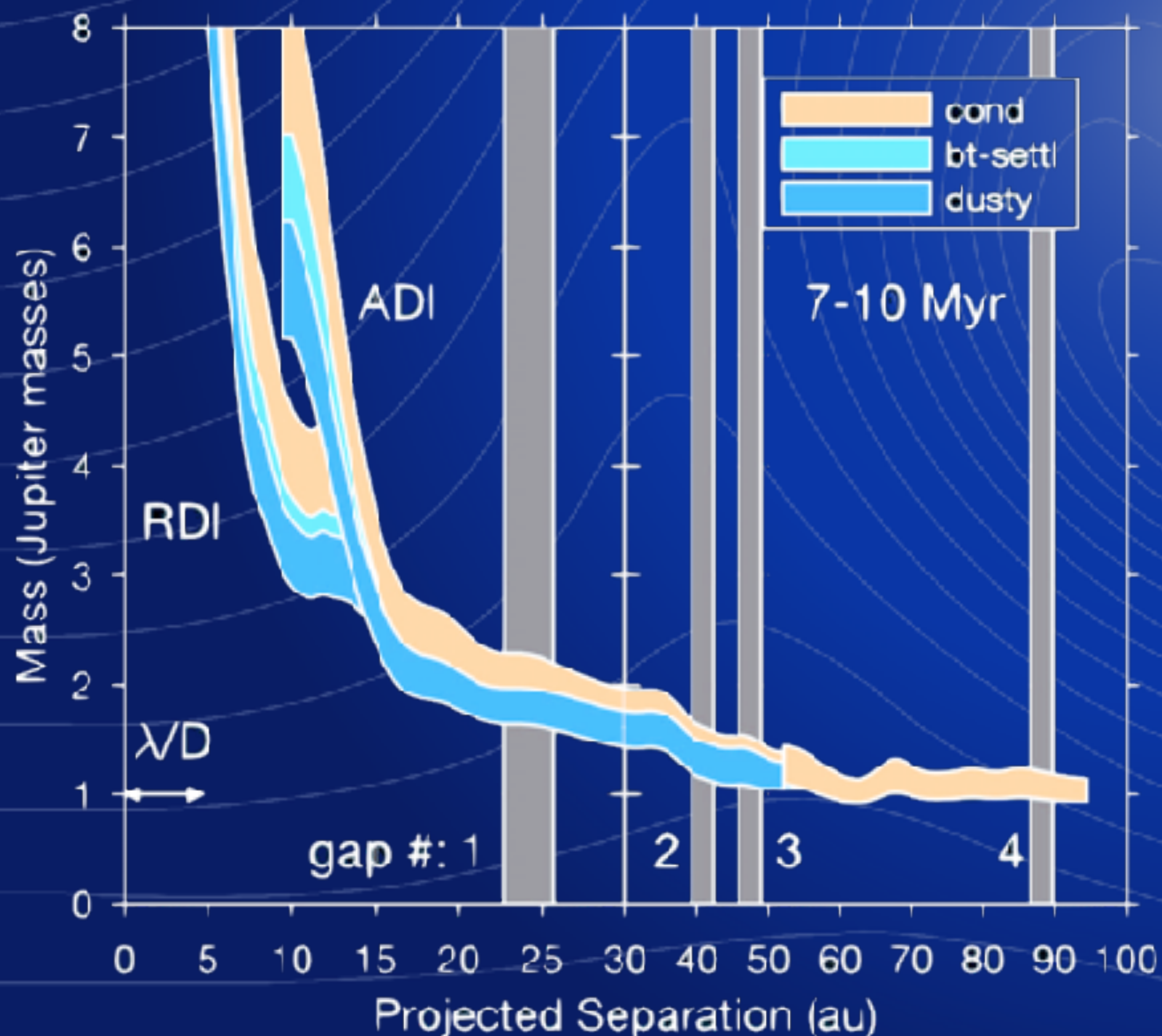


Ruane et al. (2017)

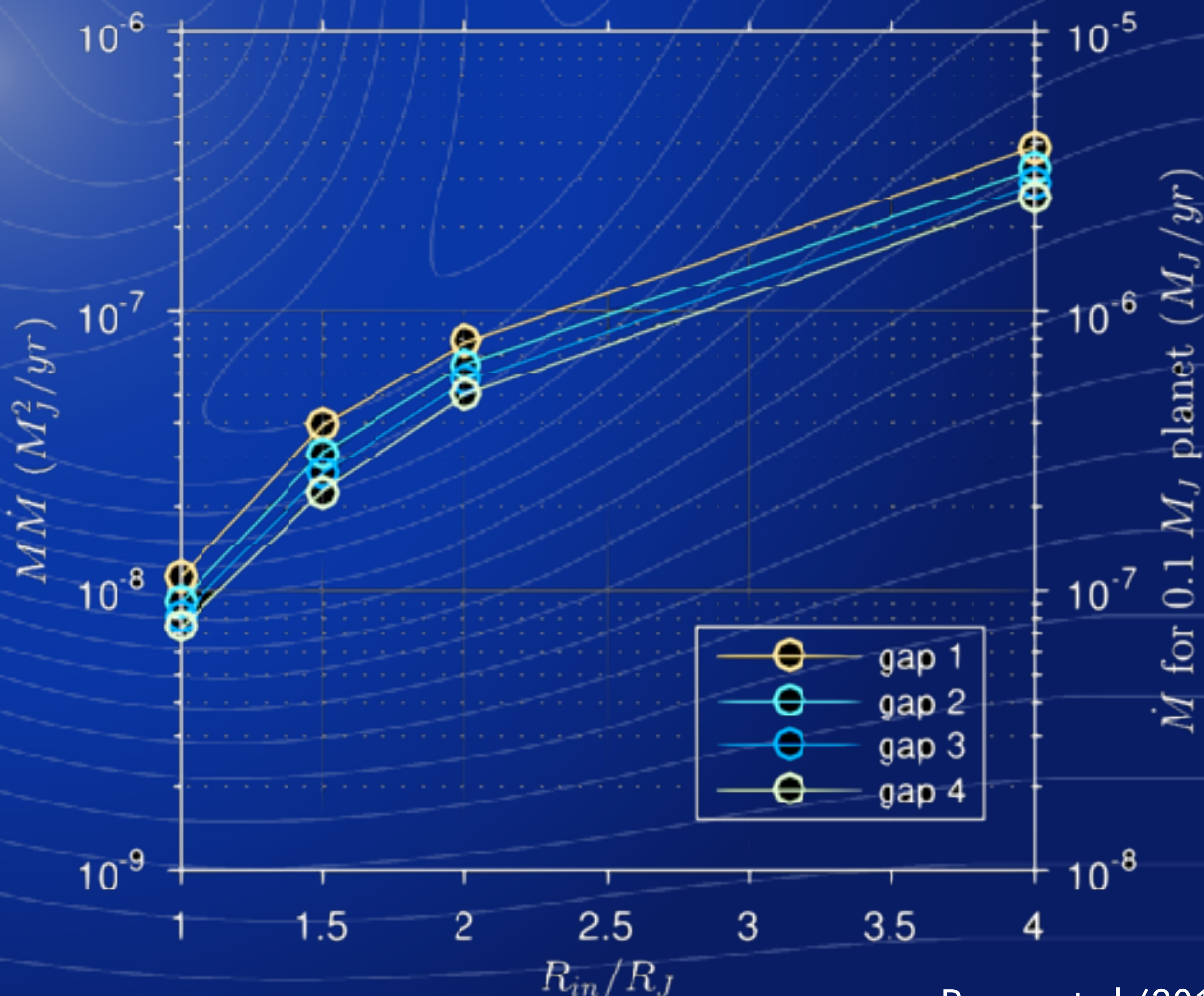
CONSTRAINING (PROTO)PLANETS IN TW HYA DISK

- protoplanet with circumplanetary disk truncated at ~1R_{Jup} presently accreting at a rate insufficient to form a Jupiter-mass planet

non-accreting planets



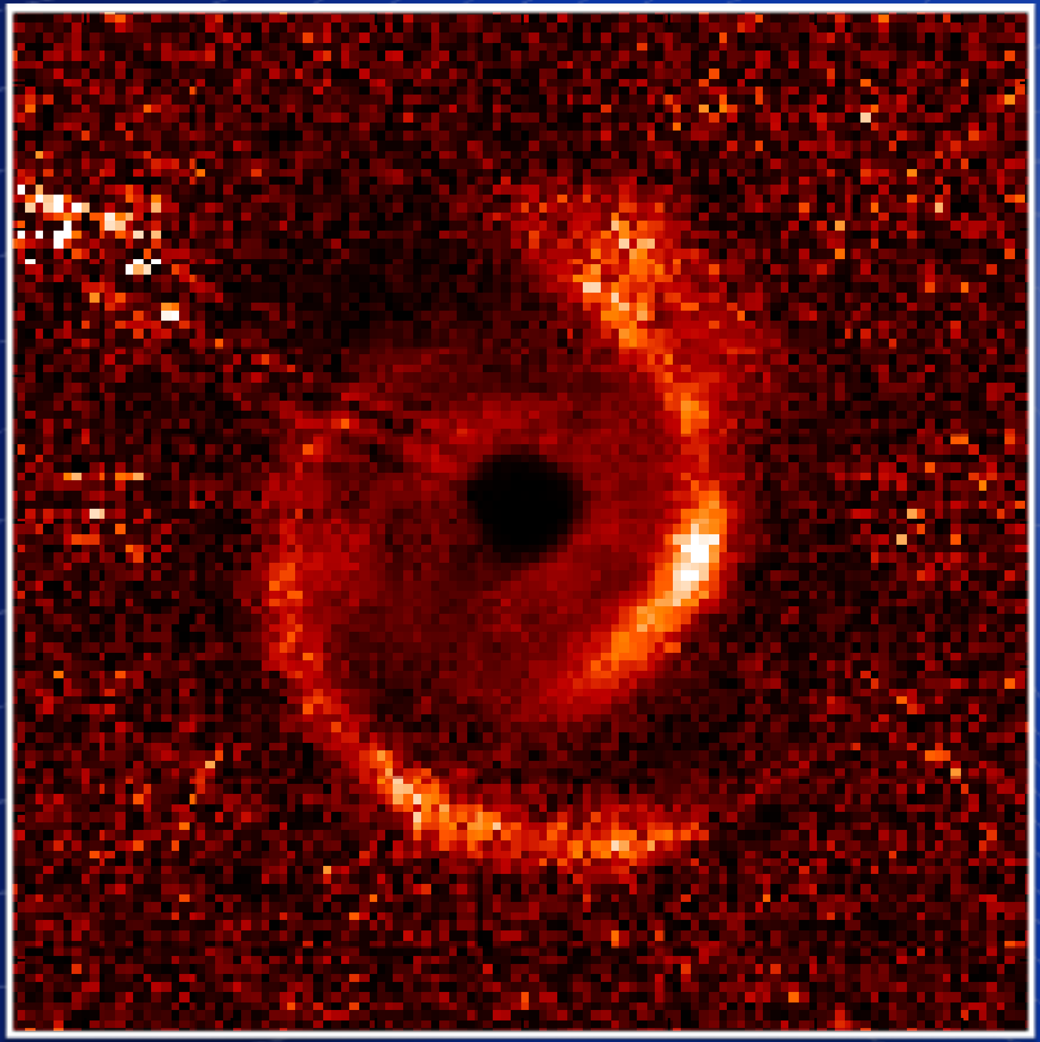
accreting planets



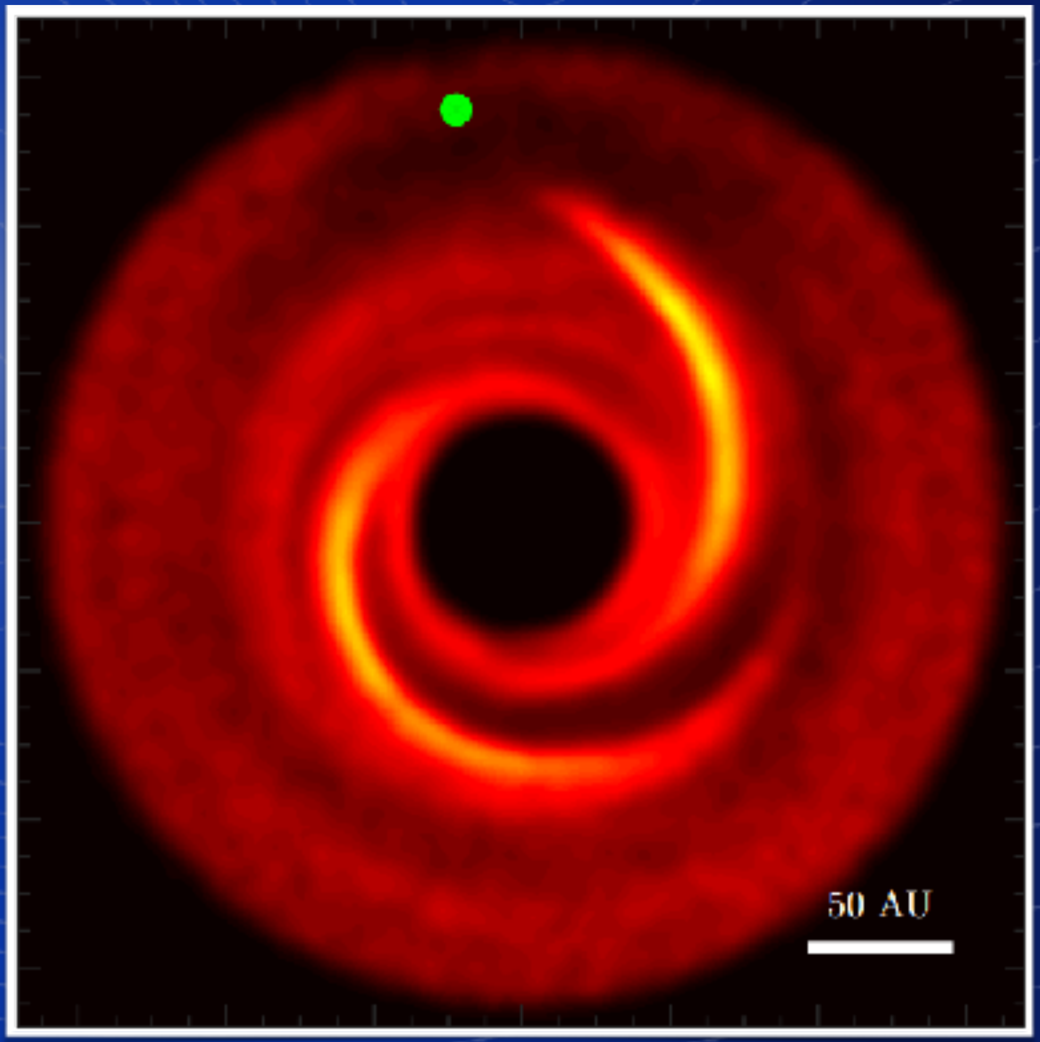
Ruane et al. (2017)

TRANSITION DISK SURVEY (NIRC2 & NACO)

SPHERE/IRDIS Y band polarimetry (Benisty et al. 2015)

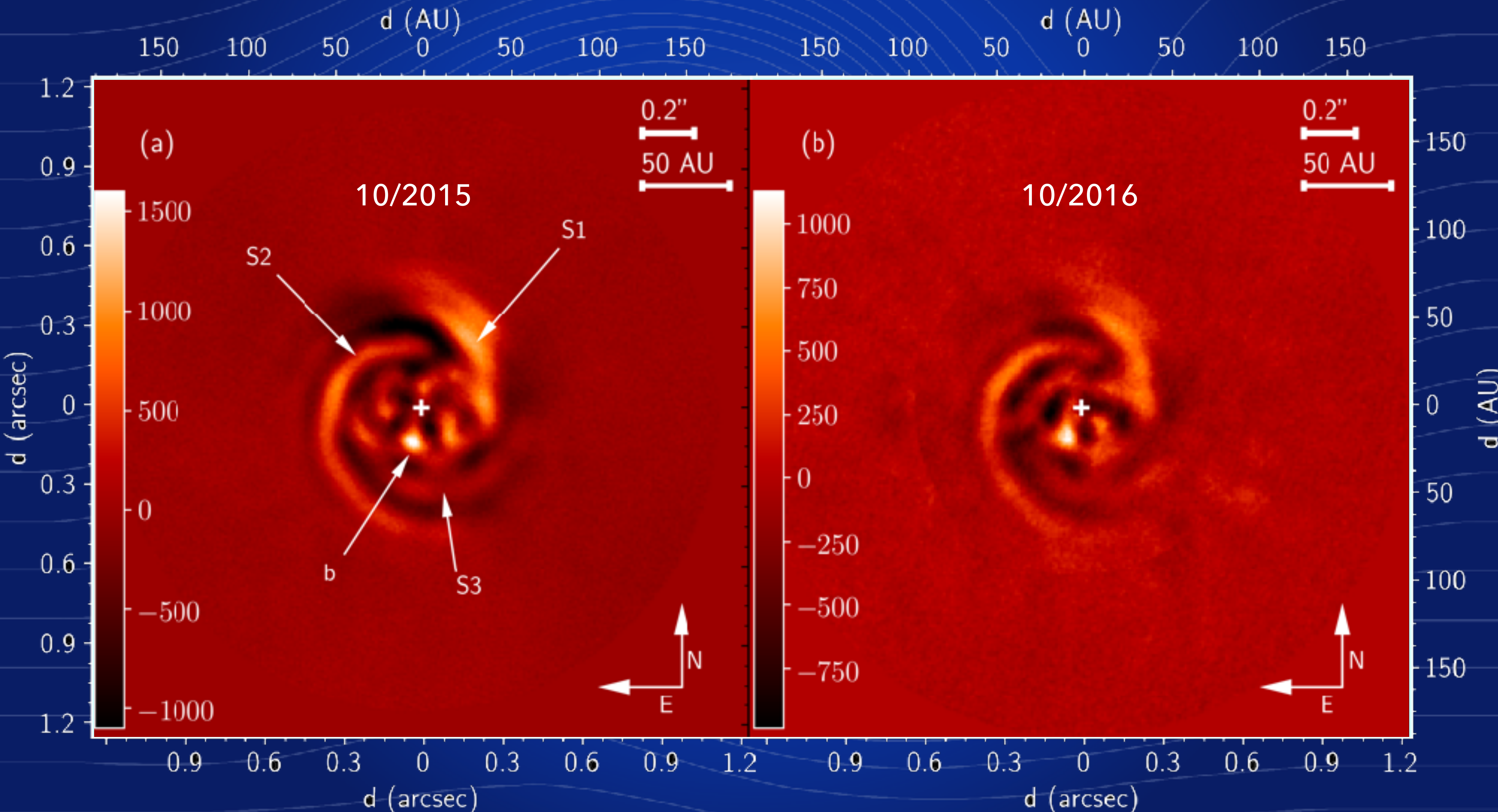


Protoplanet prediction (Dong et al. 2015)



goal: search for protoplanets at the origin of disk structures

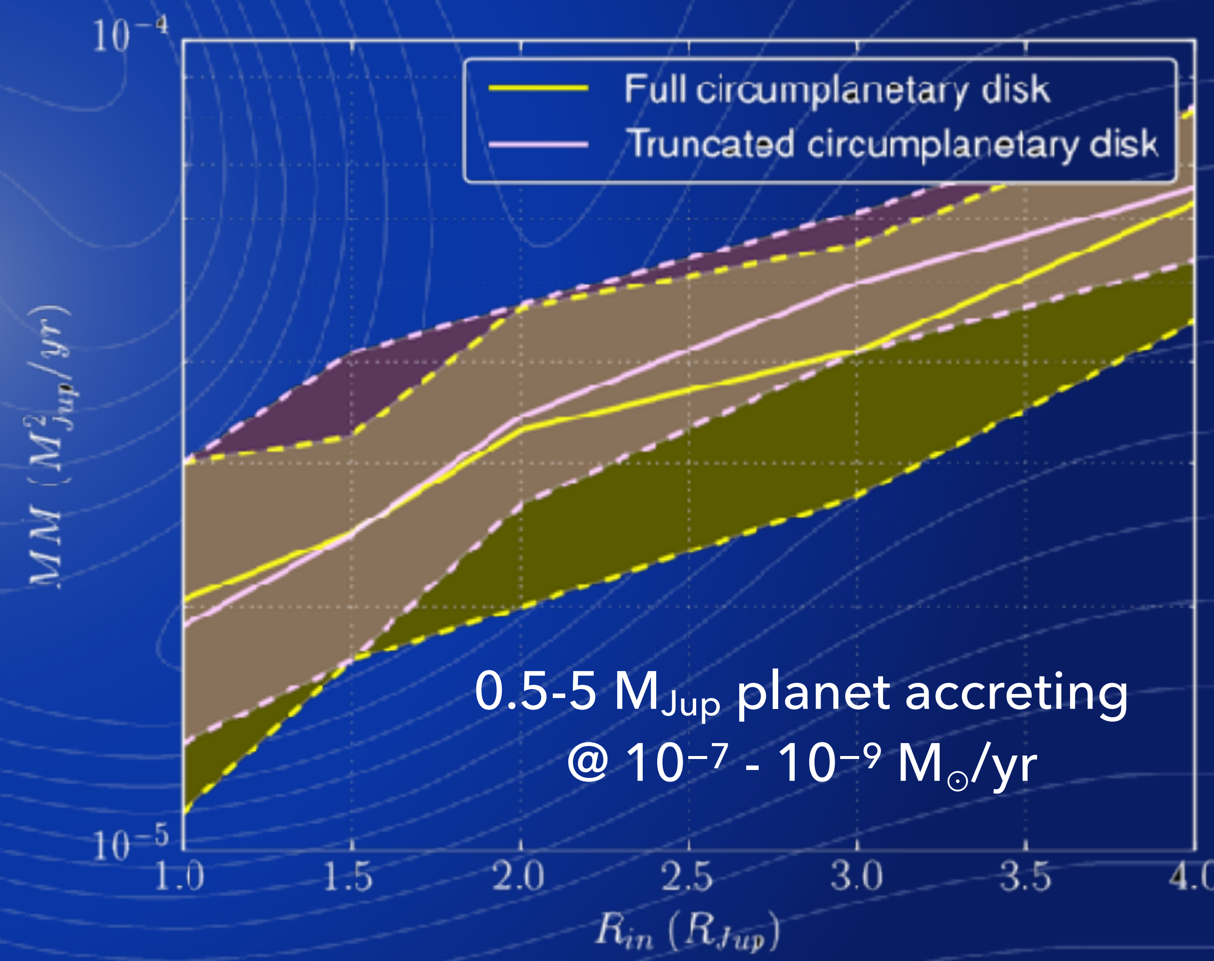
THE KECK/NIRC2 + VORTEX VIEW OF MWC758



Reggiani et al. (submitted)

MWC758: YET ANOTHER PROTOPLANET CANDIDATE?

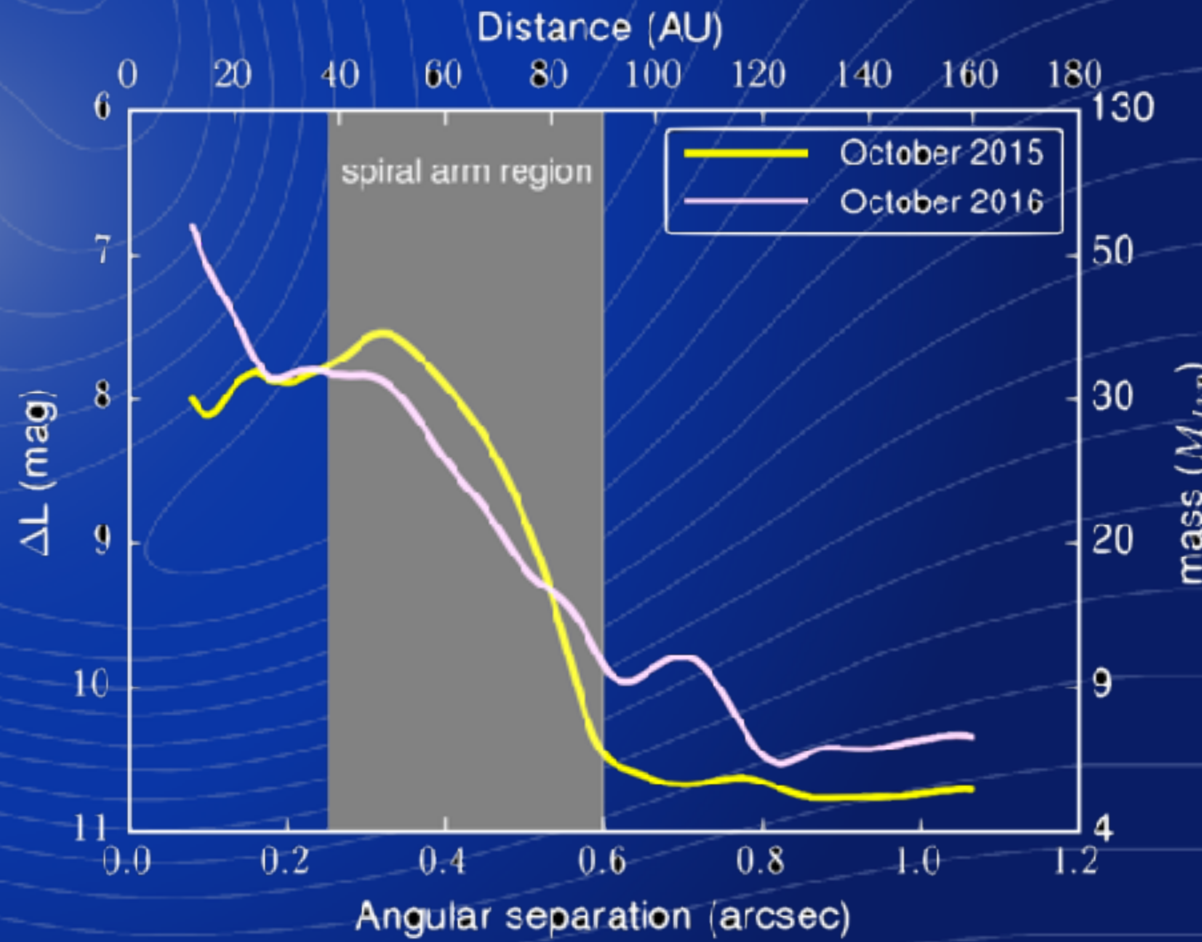
- main properties
  - 0.1'' separation (20 au), ΔL = 7
  - two epochs: PA difference consistent with Keplerian rotation in 1 yr
- low probability for bckg star
- companion? needs to be <6 M_{Jup}
  → not purely photospheric emission
- conclusion: accreting protoplanet or disk feature?
  - no polarized disk emission there!



Reggiani et al. (submitted)

MWC758: ORIGIN OF THE SPIRALS?

- now three spiral arms to reproduce with models
- driven by protoplanet?
  - outer planet? most likely explanation based on models, but strong constraints from observations (< 6 M_{Jup})
  - inner planet? might explain one spiral, but not all three

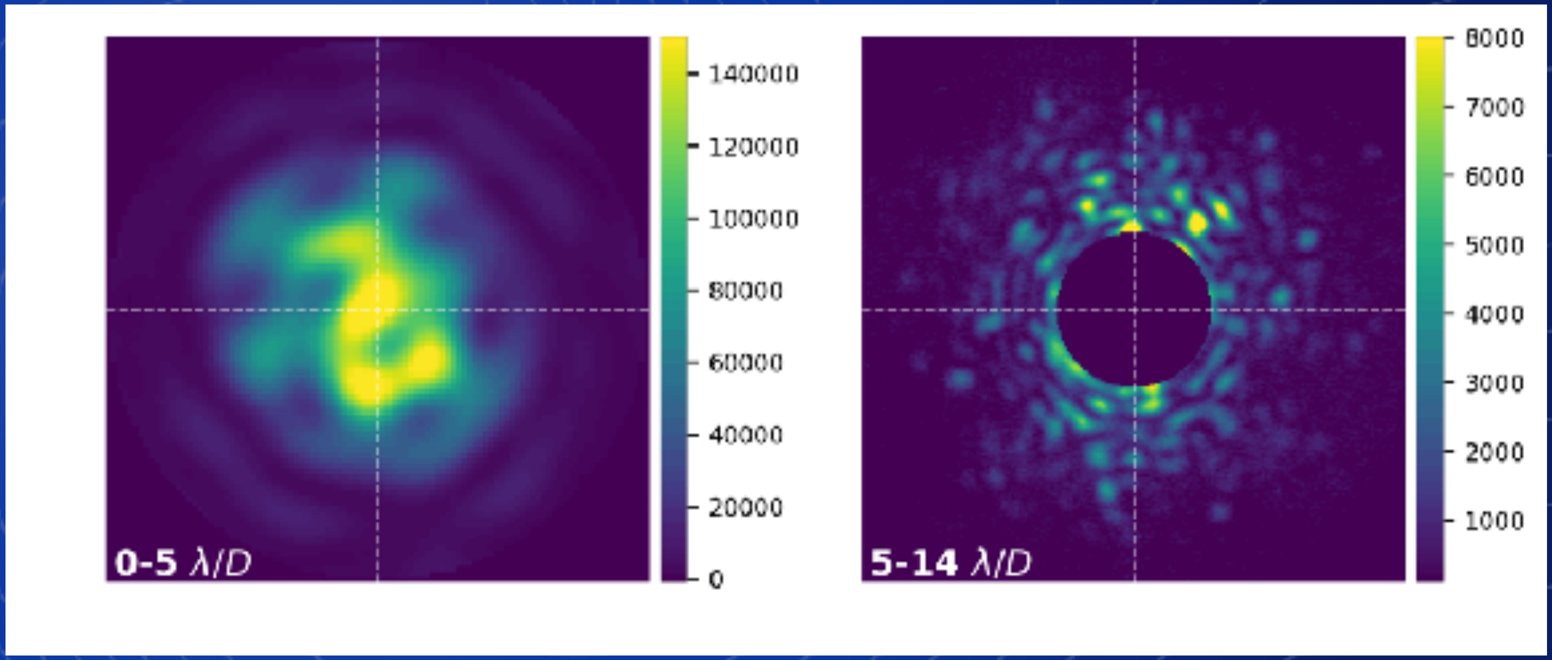


Reggiani et al. (submitted)

HOW TO BETTER EXPLOIT THE DATA?

- interesting science at 1-3 λ/D
  - strongly affected by residual speckles
  - non-Gaussian noise –> more false positives
  - hard to validate candidates

NIRC2+vortex image sequence

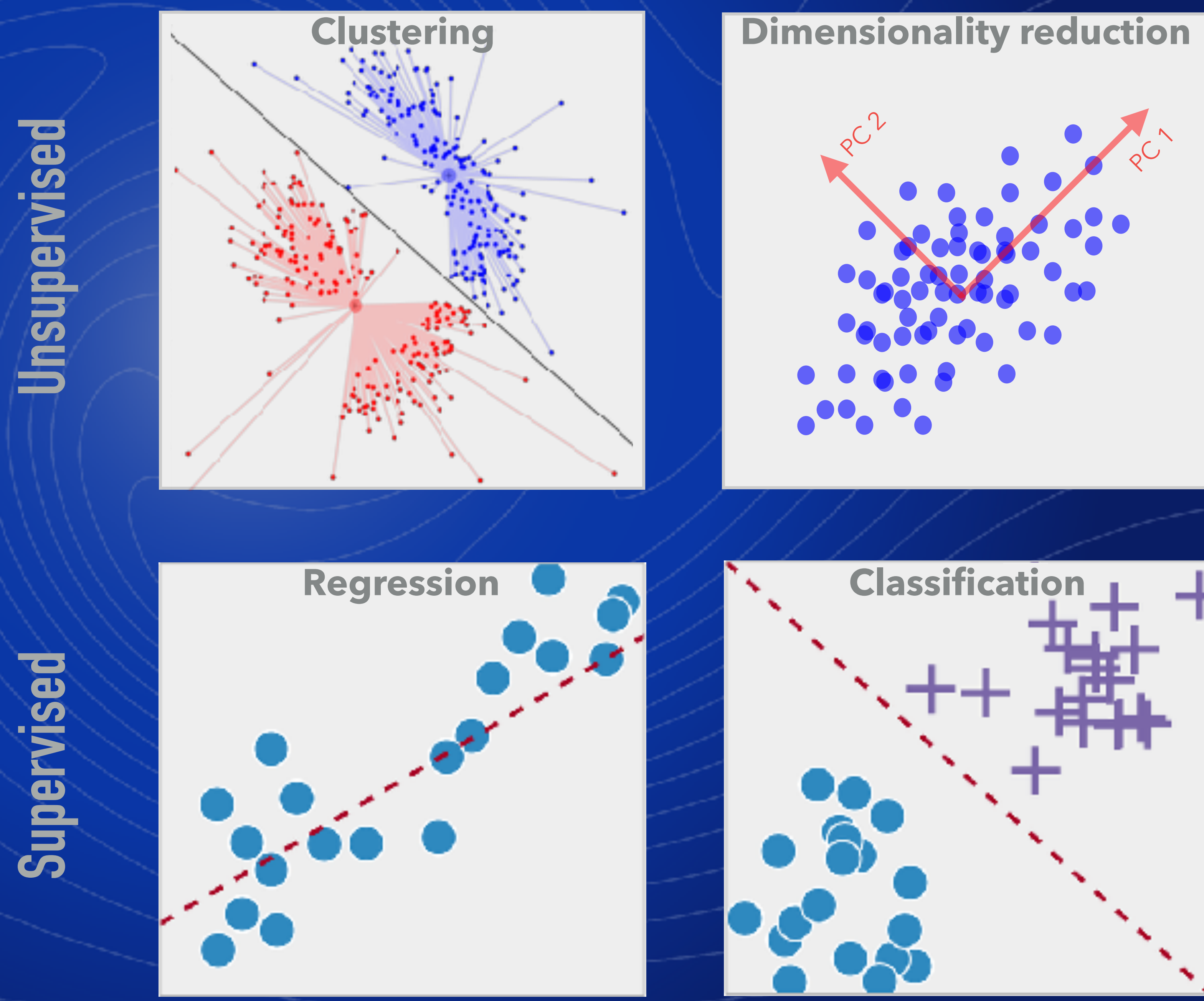


- ADI-based techniques produce SNR, but do not inform on nature of the source
- machine learning can help

IMAGE PROCESSING WITH MACHINE LEARNING

MACHINE LEARNING IN A NUTSHELL

- construction of algorithms that can learn from, and make predictions on data



SUPERVISED LEARNING

- goal: learn function f mapping input samples $\mathcal{X}$ to labels $\mathcal{Y}$ given a labeled dataset $(x_i, y_i)_{i=1,\ldots,n}$:

$$\min_{f \in \mathcal{F}} \frac{1}{n} \sum_{i=1}^{n} \mathcal{L}(y_i, f(x_i)) + \lambda \Omega(f)$$

- mapping function f based on (deep) neural network
  - layers of neurons whose parameters can be tuned to approximate a complex function
  - DNN can be trained with labeled datasets
- problem: need labels & large training sample!

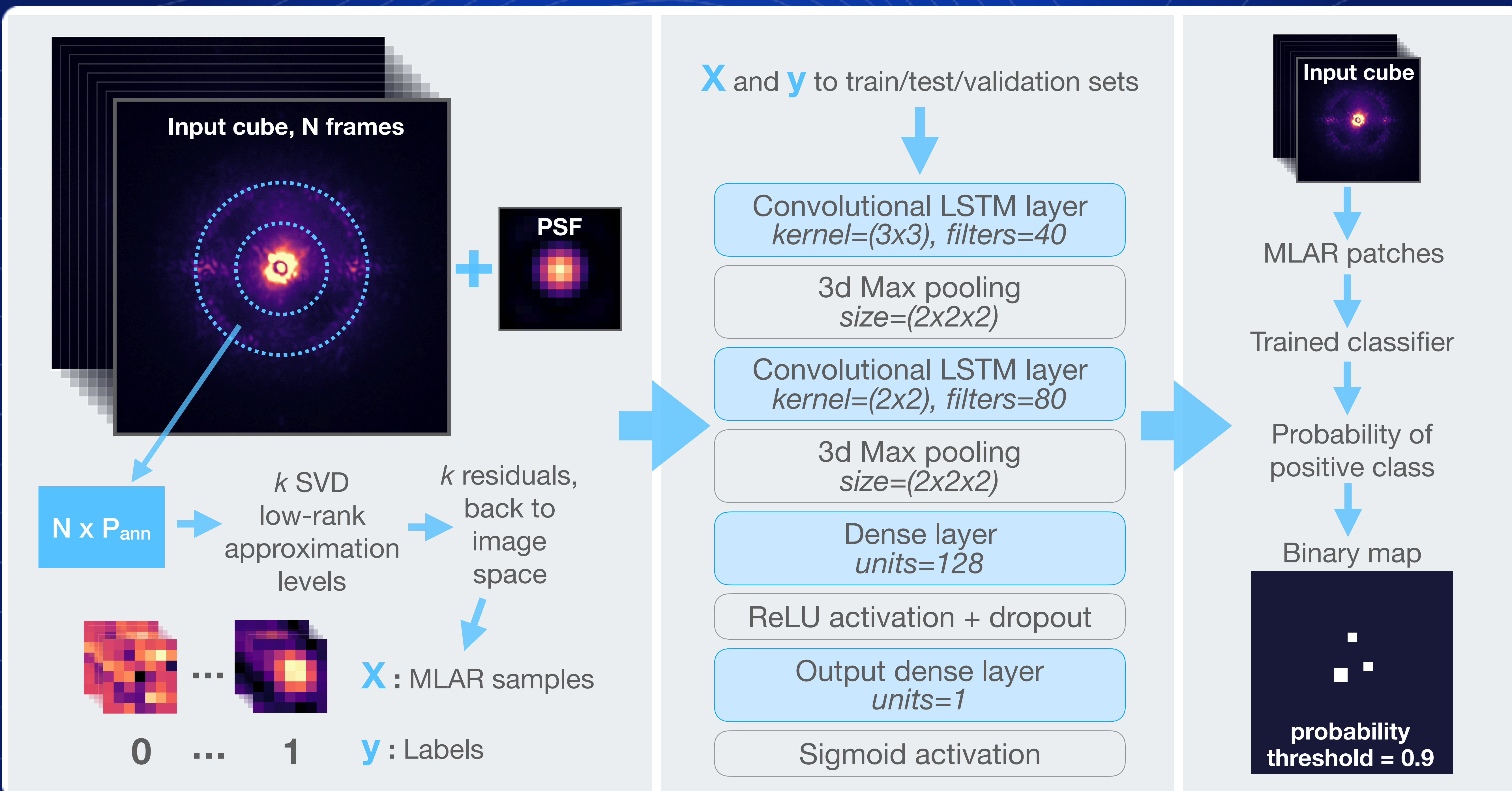
SUPERVISED DETECTION OF EXOPLANETS

Gomez Gonzalez et al. (submitted)

1. generation of labeled data

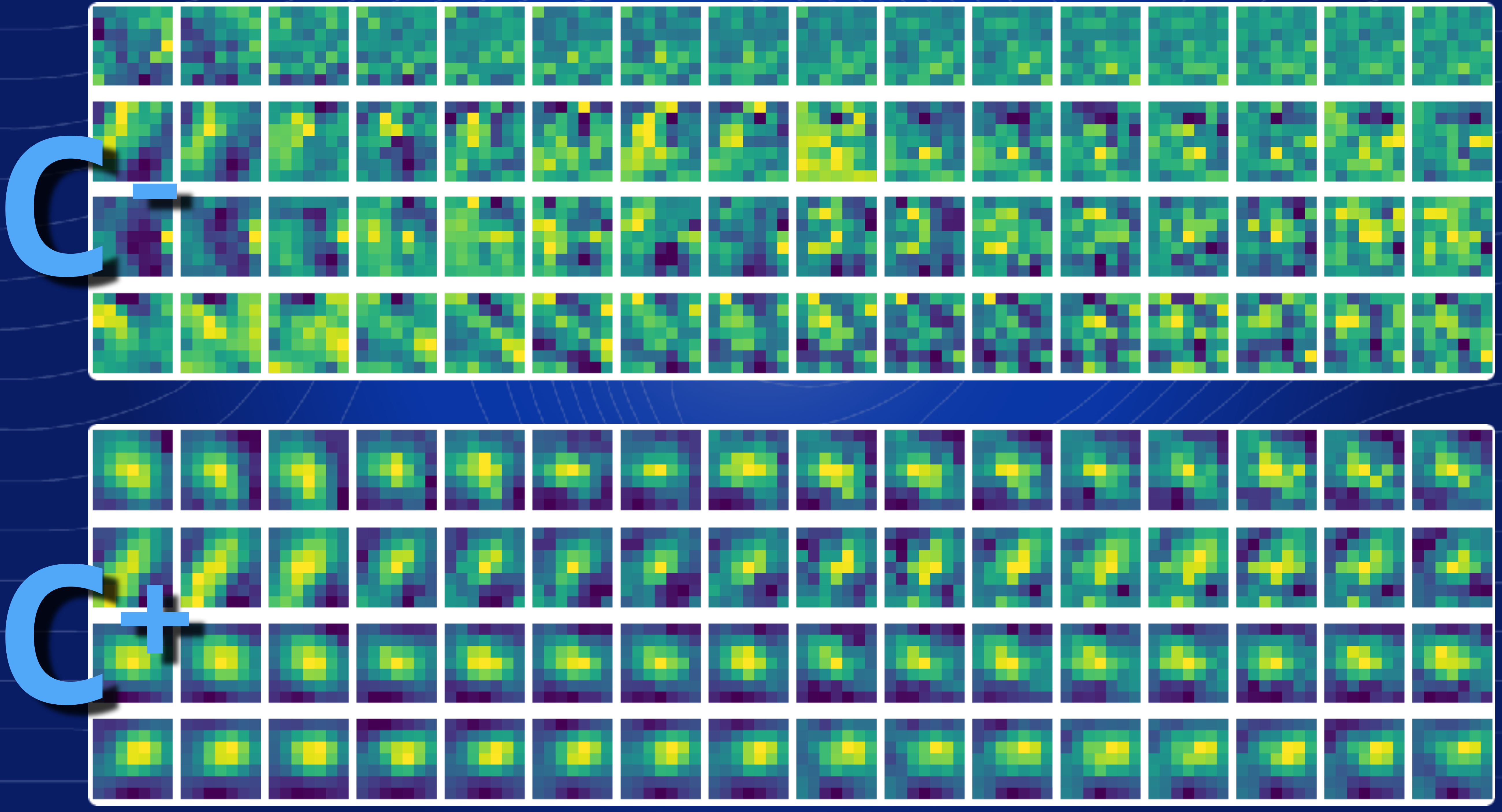
2. training the DNN

3. prediction



LABELED DATASET

Labels: $y \in \{c^-, c^+\}$



SUPERVISED DETECTION OF EXOPLANETS

Gomez Gonzalez et al. (submitted)

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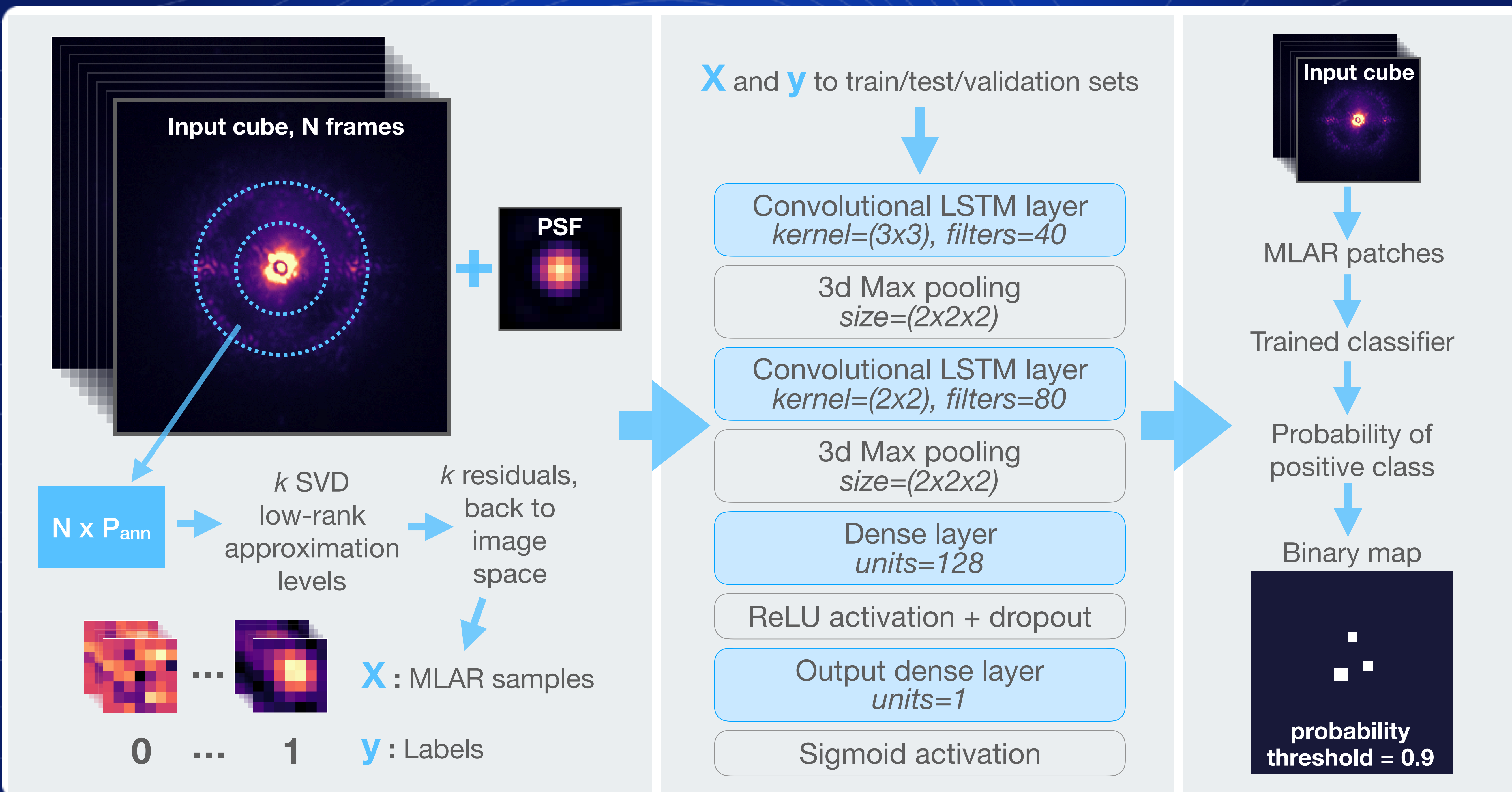
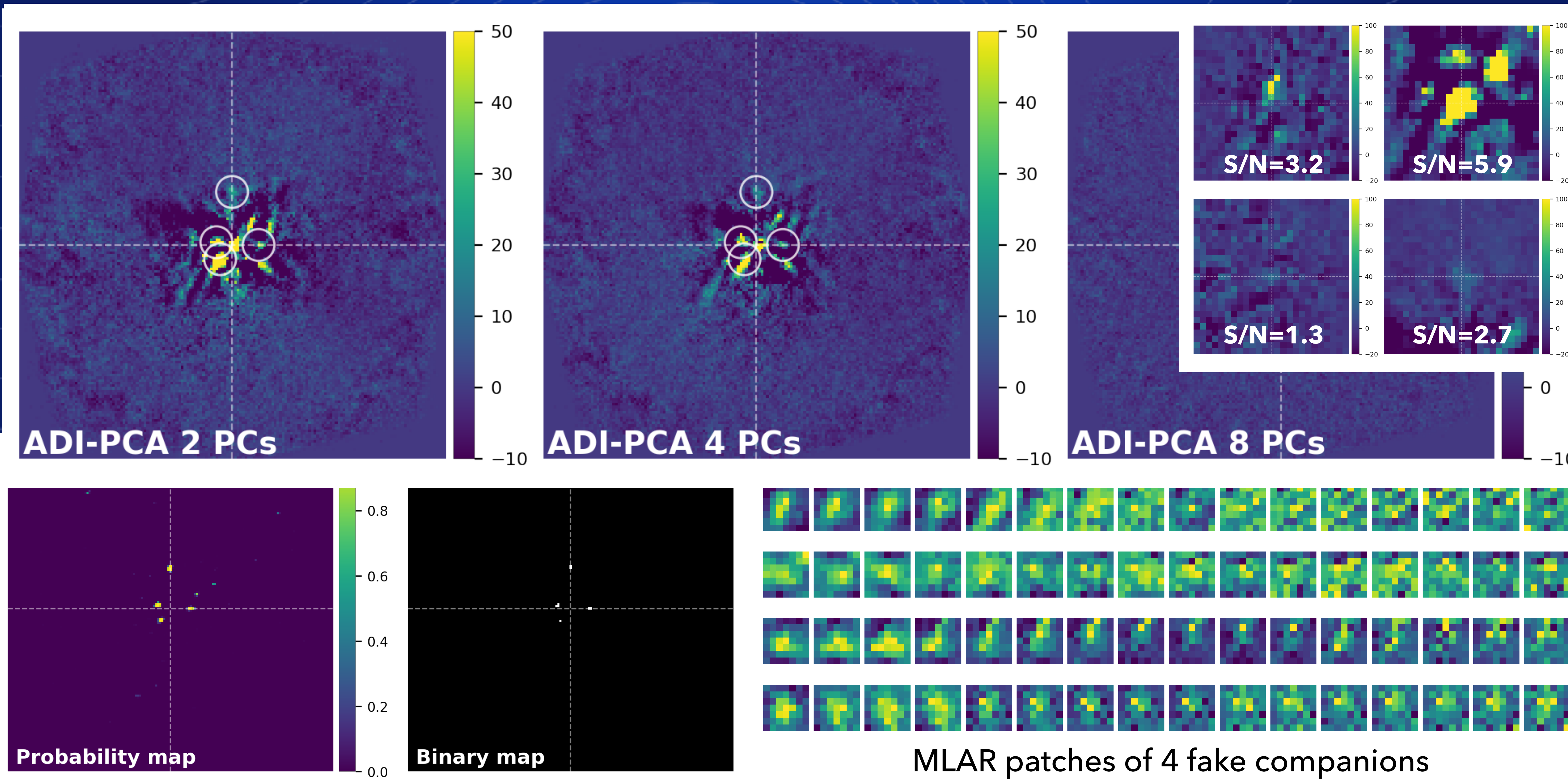
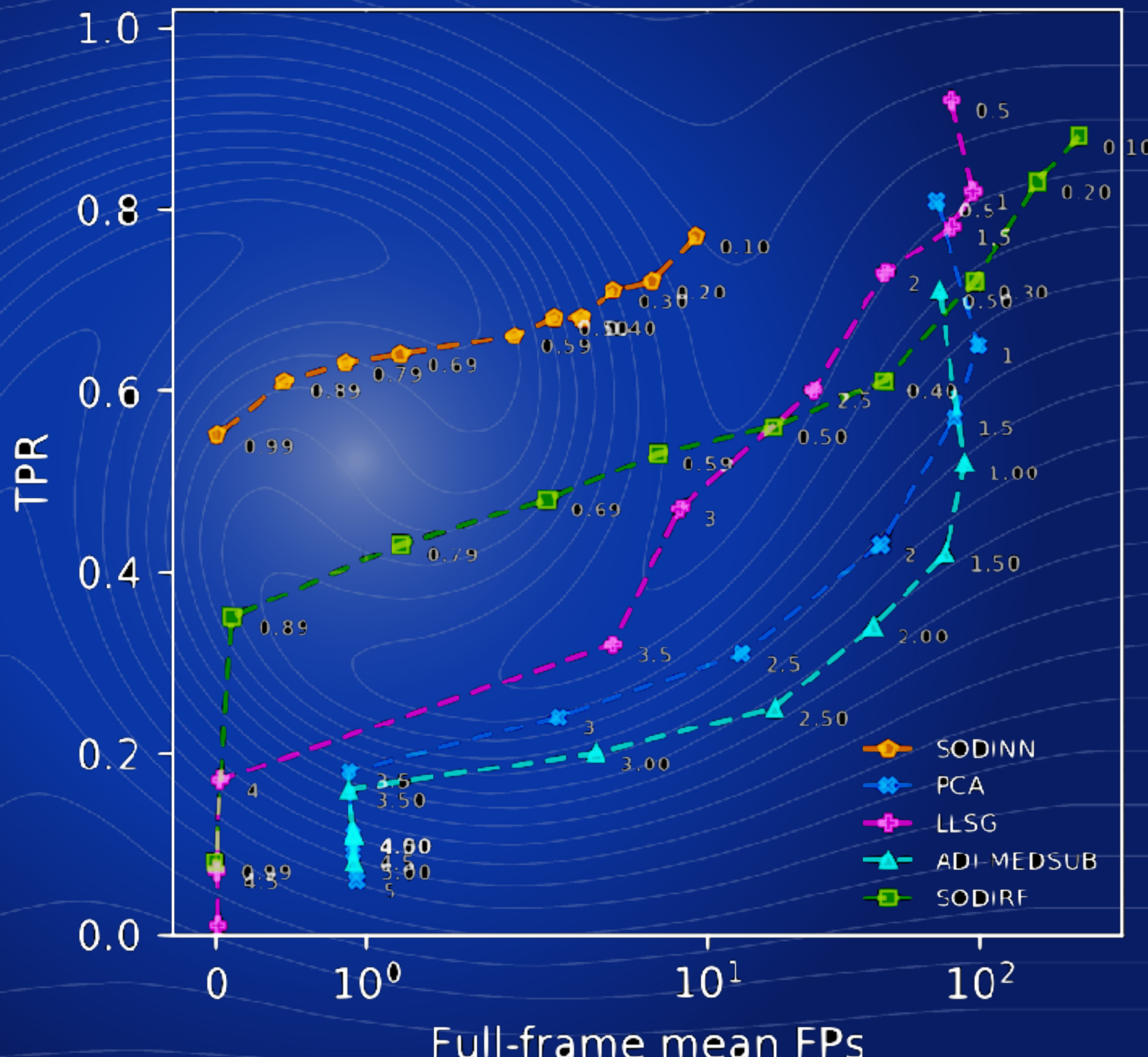


TEST WITH INJECTED COMPANIONS (SPHERE/IRDIS)



ROC CURVES

- Separation
  - 2 - 3 λ/D
- Contrasts
  - 2.9×10^{-5} to 1.4×10^{-4}



VORTEX

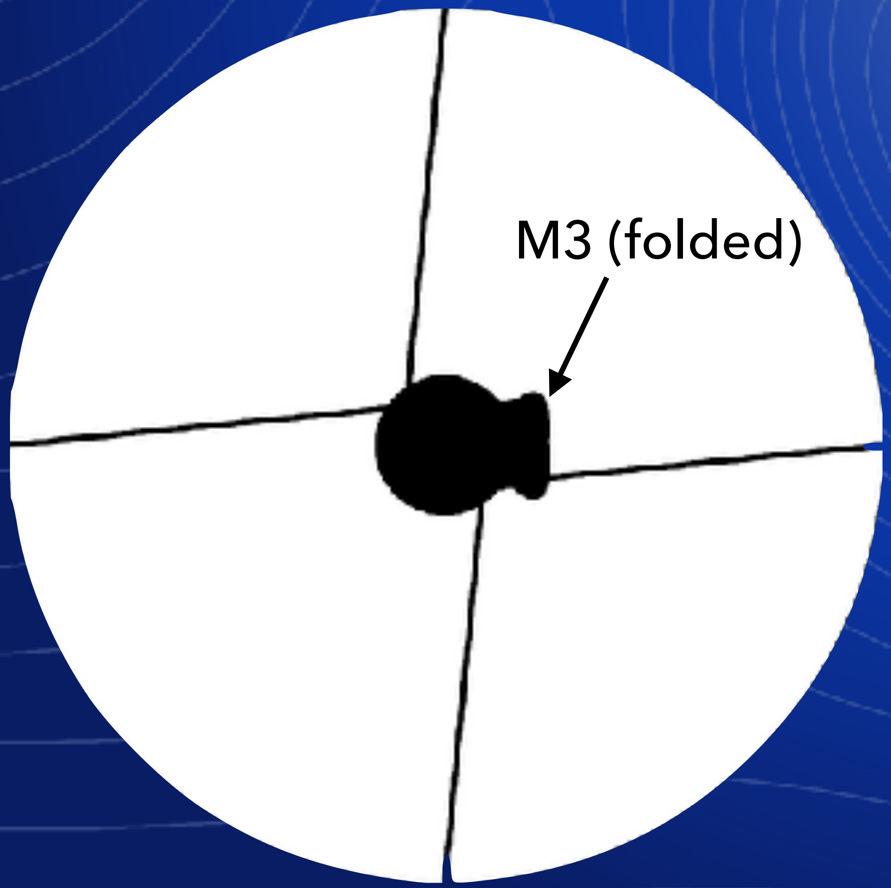
FUTURE PROJECTS

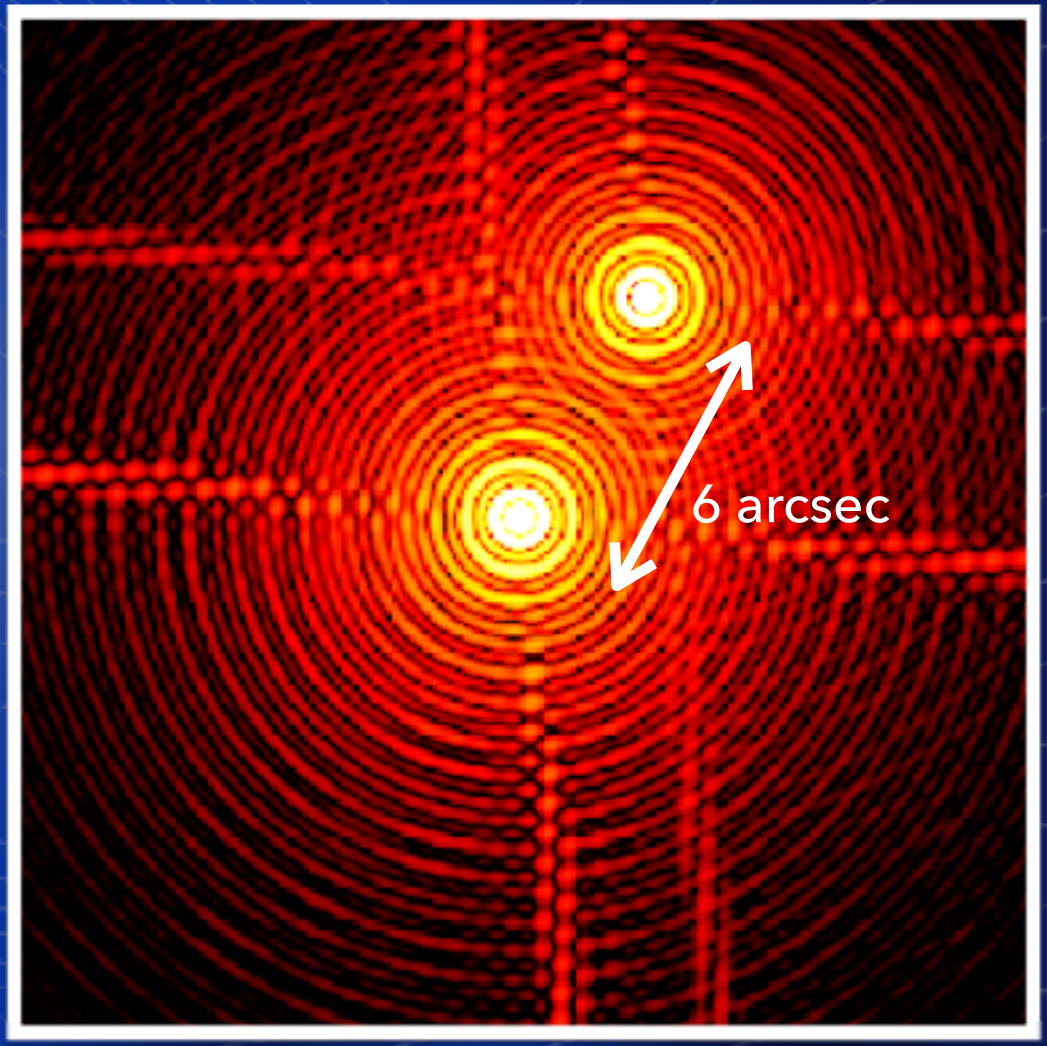
NEAR – NEW EARTH IN THE ALPHA CENTAURI REGION

- ESO project funded by Breakthrough Watch
  - what? search for rocky planets around α Cen A&B
  - how? refurbish VISIR and put it behind UT4+AOF
  - when? 100h observing campaign in mid-2019
- vortex team contribution
  - provide optimized AGPM for 10-12.5μm filter
  - design optimized Lyot stop
  - develop closed-loop pointing control with QACITS

NEAR LYOT STOP: TWO CHALLENGES

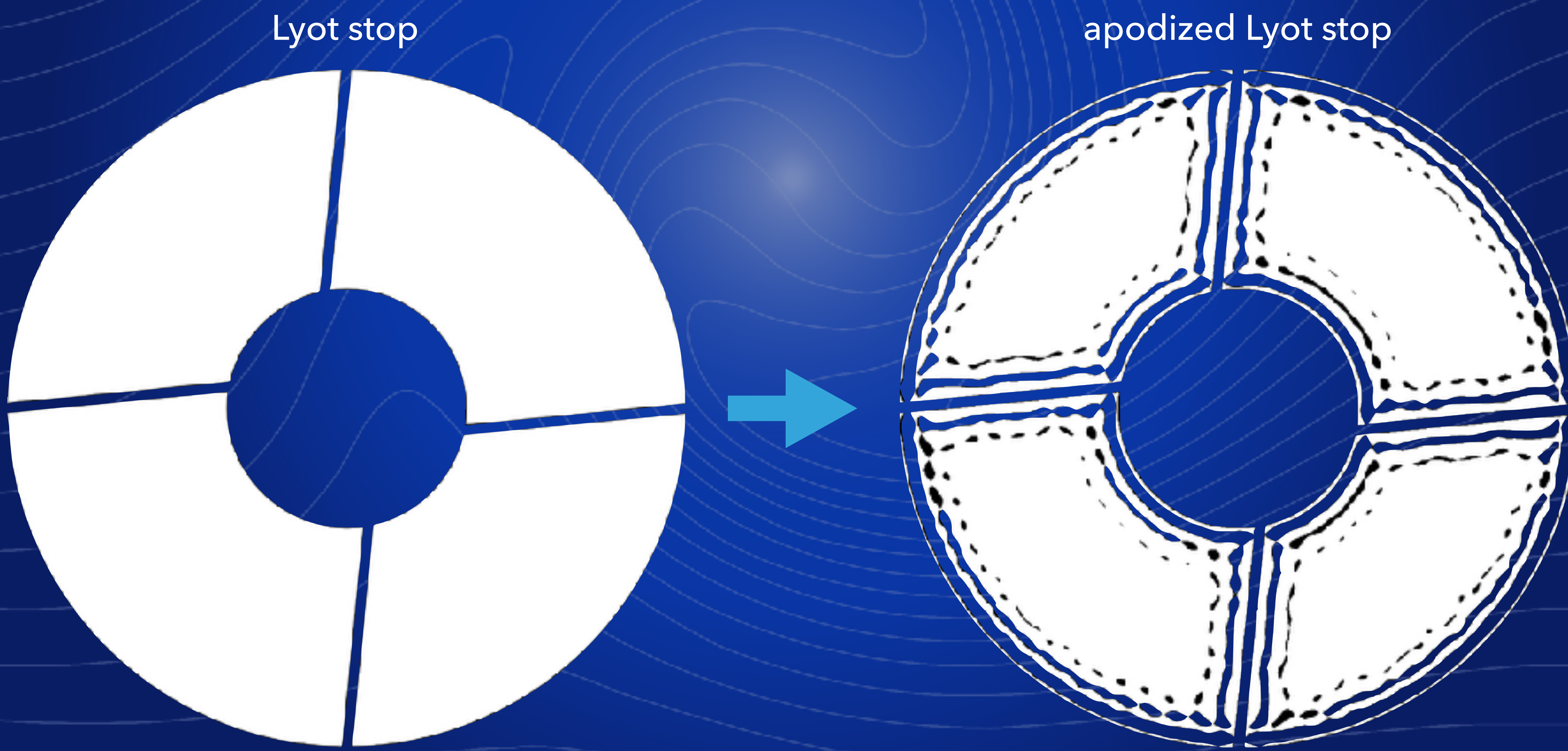
- binary target star
  - need to dim secondary star
- complicated pupil





AN APODIZED LYOT STOP

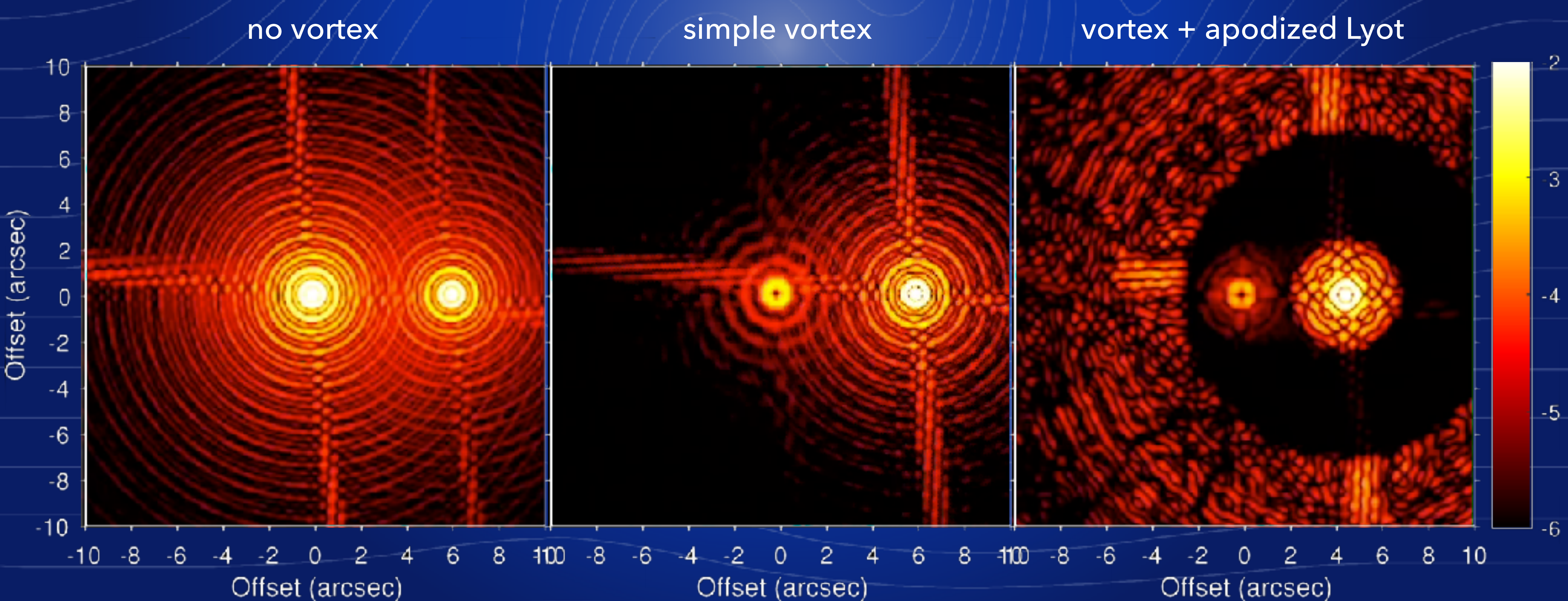
- shaped-pupil: induce dark hole from 3″ to 8″ around B



courtesy G. Ruane, AJ Riggs

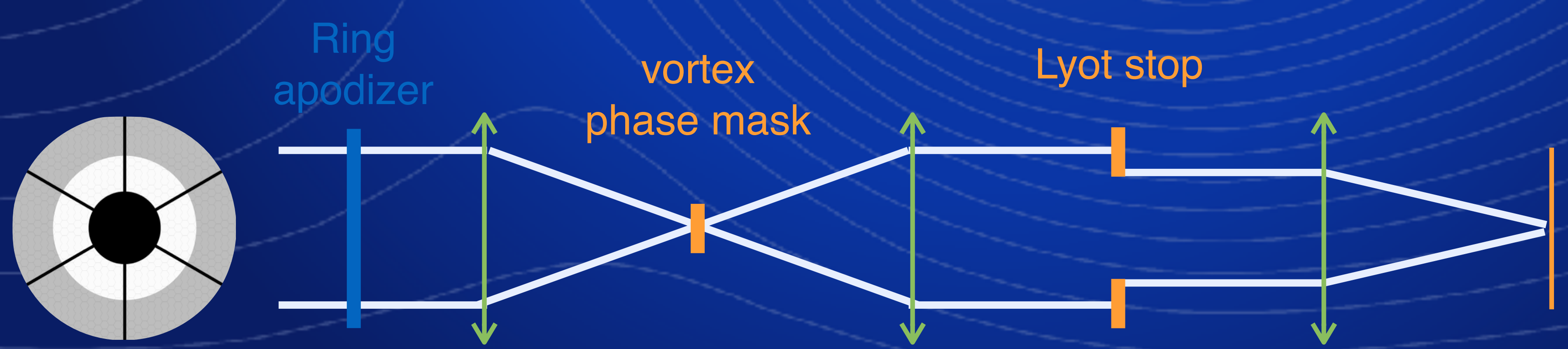
NOTIONAL IMAGES OF ALPHA CENTAURI SYSTEM

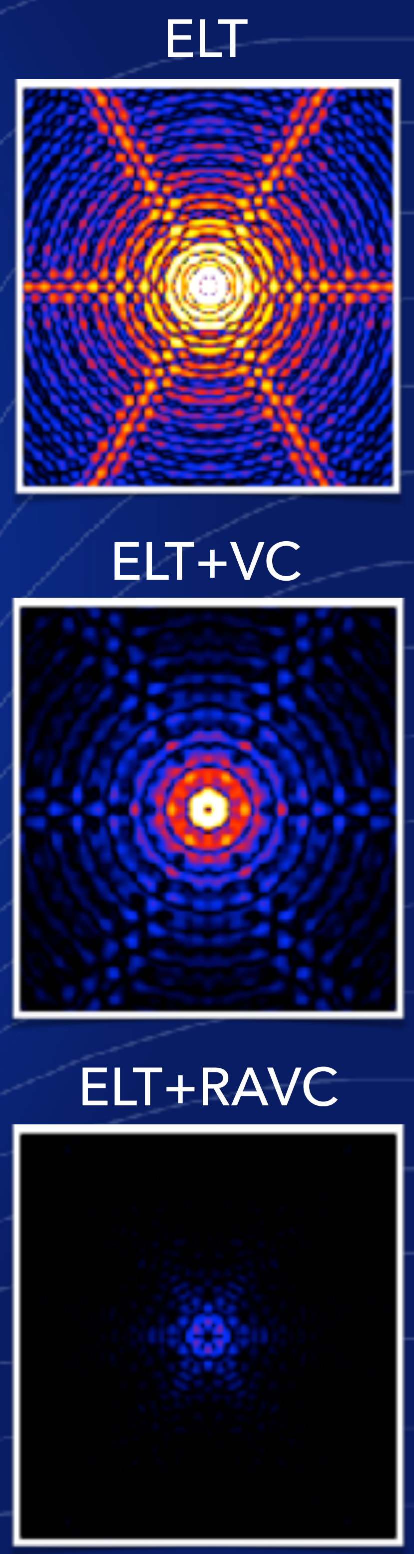
- habitable zone at 0.8″ - 1.1″ (A) or 0.5″ - 0.65″ (B)
- contrast around 10^{-6} for 2 $R_{\oplus}$ planet



NEXT STEPS: VLT/ERIS AND ELT/METIS

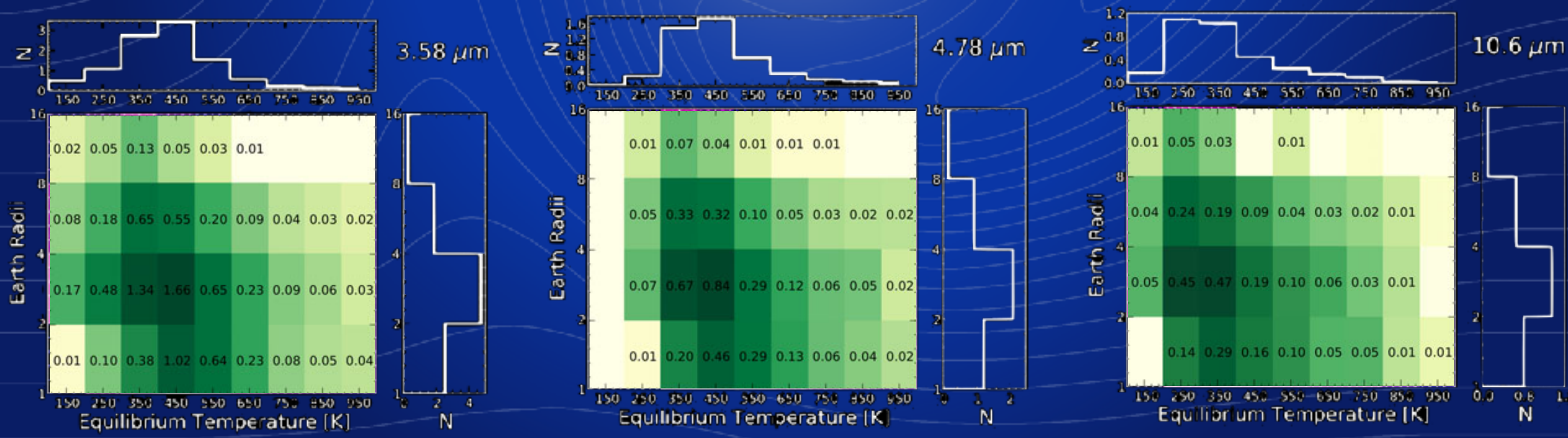
- ERIS: L & M band AGPMs
  - standard vortex coronagraph with simple Lyot stop
- METIS: L, M & N band AGPMs
  - ring-apodized vortex coronagraph: cancels diffraction from huge central obstruction





METIS SCIENCE HIGHLIGHTS

- direct imaging of several RV planets
- potential to detect temperate rocky planets
- characterization with high-res LM-band IFS



A VORTEX UPGRADE FOR SPHERE?

- goal: open the 1-3 λ/D parameter space
  - increase number of detections
  - access a few RV planets
- need to identify main limitations to FQPM performance
  - component degradation?
  - effect of dead actuators?
  - low-order wavefront aberrations?
- K-band AGPM performance being evaluated

THANKS FOR YOUR ATTENTION

AND NOW . . . GAME ON!